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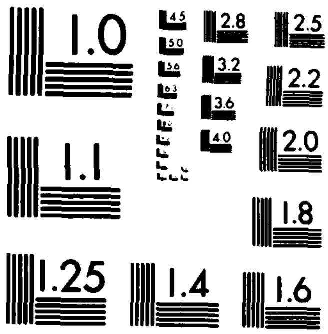

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DAVIDSON LABORATORY

Report SIT-DL-85-9-2518

March 1985

DESIGN PROCEDURES FOR LOW SPEED WATERJETS SUITABLE FOR APPLICATION IN AMPHIBIOUS VEHICLES

by

John K. Roper
Consultant

Prepared for

Code 1120
David W. Taylor Naval Ship Research
and Development Center

Under

Office of Naval Research
Contract N00014-83-C-0780

(DL Project 5154/160)

STEVENS INSTITUTE
OF TECHNOLOGY

CASTLE POINT STATION
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R-2518

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Trials performance of an axial flow pump, used for waterjet propulsion in a manned testcraft, was analyzed, compared to design predictions, and then used to modify pump design procedures as appropriate. Performance estimates have been made for a new waterjet unit for the testcraft, and also for a larger unit which could be used in a prototype high-speed amphibious vehicle.

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INTRODUCTION

The U.S. Marine Corps is supporting an effort to increase the efficiency of waterjet propulsion units in existing amphibious vehicles. Reference 1 details the design of three axial-flow pumps, including one for an existing LVTP-7A1 which runs at speeds below 8 miles per hour. The other two pumps were designed to provide cavitation-free performance at propulsive coefficients in the region of 40 to 45 percent at a vehicle water speed of 20 mph. State-of-the art composite material technology was used wherever possible to reduce weight.

Next, a manned testcraft was constructed to evaluate a 14-inch diameter waterjet unit at vehicle speeds up to 25 mph in water. Reference 2 presents an analysis of initial trials conducted in August 1983.

A more comprehensive trial of the testcraft was run in July 1984 and test data have been reduced and analyzed. This report presents:

- A comparison of waterjet design predictions and July 1984 trial results.
- A waterjet design procedure, modified as appropriate to reflect trial experience.
- Performance estimates for a new 14-inch diameter axial-flow pump, designed for the existing testcraft.
- Performance estimates for a 16-inch diameter axial-flow pump unit, designed for possible use in a prototype high-speed amphibious vehicle.

This work was performed under Office of Naval Research Contract N00014-83-C-0780. Mr. Walter Zeitfuss of the U.S. Marine Corps Program Office, Code 112 DTNSRDC, was technical monitor of the project.

PREDICTED PUMP PERFORMANCE CHARACTERISTICS

Design procedures detailed in Reference 1 were applied to predict head losses in the waterjet system as follows.

a. For inlet entrance lengths of 33, 23 and 19.5 inches

- Head losses: at entrance; in duct; and due to impeller shaft.

b. Losses due to duct-to-casing transition, shaft bearing tube and struts.

c. Losses due to friction in impeller casing.

d. Losses in 10.5-inch and 12.25-inch exit diameter nozzles; losses due to drag of pitot tubes and pitot tube rack.

All of these head losses were expressed as functions of flow rate Q. Total head loss, less inlet head recovery as a function of vehicle speed, must equal the pump head required H_p. A prediction of power required to drive the pump is:

$$SHP = H_p \, Q \, \rho g / 550 \, \eta_p$$

where pump efficiency η_p was taken as 0.72 based on testcraft trial results.

Appendix A presents nomenclature for this and subsequent sections. Appendix B contains all the calculations of pump performance predictions.

ANALYSIS OF PUMP TEST RESULTS

Waterjet testcraft trials in July 1984 covered an extensive matrix of three inlet lengths, three (nozzle dia./casing dia.) ratios, and three impeller area ratios. A review of trial data showed that a detailed analysis of the 1.5 area ratio impeller coupled with the 12.25-inch exit diameter nozzle and the three inlet lengths, would furnish the most useful results for comparison with design predictions.

Accordingly, tabulations of performance data for the chosen impeller and nozzle at each of the three inlet lengths are presented on Pages C-1 through C-3 of Appendix C. Trends of waterjet thrust, SHP, and overall propulsive coefficient with testcraft speed are charted on pages C-4, 5 and 6 respectively. Bollard pull test results for pump efficiency η_p and impeller advance coefficient J are charted against SHP on Pages C-7 and C-8 respectively. The trends show that η_p and J are reasonably constant with SHP, and therefore, $\eta_p = 0.72$ and $J = 0.82$ were chosen for use in subsequent design predictions.

Next, a tabulation was prepared to show a comparison between measured bollard pull and predicted jet thrust as calculated from measured flow velocity, Page C-9. A chart of measured and predicted thrust versus

flow rate Q shows good agreement between the two sets of thrust values, Page C-10.

Inlet losses, in the bollard test condition were predicted by using the relationships developed in Appendix B and summarized on Page B-15. Predicted losses were then compared to static head measurements taken at the aft end of the inlet duct, for each of the three inlet lengths, Pages C-11 through C-16. Good agreement between predicted and measured head loss in the three inlets is demonstrated for the bollard test condition.

Actual head recovery in the inlet was assumed equal to the difference between inlet loss at forward speed and inlet loss at zero speed (bollard pull test) at a given flow rate Q. Tabulations on Pages C-17, 18 and 19 list measured static head at the aft end of the inlet duct during speed runs for each of the three inlet lengths; also listed are flow rate Q and craft speed. Bollard test inlet loss was then calculated by using the inlet loss prediction relations, Page B-15, and measured flow rate Q. Speed test inlet loss was determined from measured static head in the inlet.

A chart on Page C-20 presents head recovered, H_o, versus craft speed V_o. Actual test values of H_o are compared to a predicted curve of H_o based on an assumption of a 100 percent recovery of dynamic head $V^2/2g$. The chart shows that 100 percent dynamic head recovery is a reasonable assumption.

Total pump head H_p was determined from measurements of impeller shaft thrust T_s by:

$$H_p = T_s/\rho g A$$

where casing area A = 1.087 square feet. Total pump head required was predicted using measured flow rate Q and vehicle speed V_o in the equations summarized on Page B-15. Tabulations of measured and predicted pump head are presented on Pages C-21, 22 and 23. A chart on Page C-24 shows good agreement between measured and predicted H_p.

Shaft horsepower SHP was determined from impeller shaft torque and revolution measurements. An SHP prediction was obtained for each test run by using measured flow rate Q and predicted pump head H_p in:

$$\text{Predicted SHP} = H_p Q \rho g/550\eta_p$$

where a pump efficiency $\eta_p = 0.72$ was chosen on the basis of bollard pull test results. Tabulations of Actual and Predicted SHP are given on pages C-25 and C-26; a chart of Predicted versus Actual SHP, Page C-27, shows

generally good agreement between the two SHP values.

Cavitation Inception

This waterjet propulsion system uses a marine-type propeller as the impeller of an axial flow pump. In evaluating cavitation inception limits, cavitation criteria for pumps and for marine propellers were used.

Reference 3, for example, defines the term "net positive suction head" or NPSH as the excess of absolute pressure over vapor pressure at a pump inlet, and also cites a dimensional characteristic "suction specific speed", S, as a useful index of pump rating:

$$S = N\sqrt{Q'} \,/\, (NPSH)^{.75}$$

N = shaft rpm

Q' = flow rate, gpm

$(NPSH)$ = net head, ft

For application to the waterjet system, the equation has been adapted as follows:

$$S = 21.19\, N\sqrt{Q} \,/\, (H_{IS} - H_{VAP})^{.75}$$

where: Q = flow rate, cu.ft/sec

H_{IS} = static head in inlet, ft abs

H_{VAP} = head equivalent of vapor pressure, ft abs

Pages C-28 through C-30 show tabulations of S and impeller shaft thrust coefficient K_T for the 1.5 area ratio impeller/12.25 inch nozzle and three inlet lengths. K_T is charted versus S on Page C-31.

As shaft speed N increases, Q increases and net head at the inlet decreases, resulting in a large increase in S. The chart shows that:

- K_T is essentially constant as S increases for all bollard pull test runs.
- K_T gradually decreases as S increases for all speed runs.

Cavitation inception would be indicated by a sharp drop in thrust coefficient at high values of S; no such drop is evident for the test conditions shown.

Next, calculations of criteria for cavitation inception on marine propellers were made for all trial data (3 impellers, 3 nozzle openings, 3 inlet lengths). Cavitation index σ is usually calculated as the ratio (net head at propeller blade tip) / (dynamic head due to resultant tip velocity) However, trial results have shown that advance coefficient J is essentially constant over the impeller operating range, i.e. the ratio of (axial fluid velocity) / (tangential tip velocity) is constant. This suggests that a cavitation index based on axial fluid velocity would be a useful simplification.

Pages C-32 through C-34 are tabulations of thrust coefficient K_T and conventional cavitation index σ_t based on resultant tip velocity. Page C-35 is a chart of K_T versus σ_t for all tests of the 1.50 area ratio impeller/12.25 inch nozzle with three inlet lengths. Since σ_t varies approximately as the inverse of pump specific speeds, trends of K_T as σ_t decreases are similar to trends of K_T as S increases, Page C-31.

Page C-36 shows tabulations of σ, K_T and pump efficiency η_p for bollard pull tests of the three impellers with a common nozzle (12.25 inch) and inlet length (33 inches), where σ is based on axial flow velocity at the impeller. K_T is charted versus σ on Page C-37, and η_p is plotted against σ on Page C-38. In each chart, there is a sharp drop in thrust coefficient and pump efficiency for the 1.0 area ratio impeller at the highest flow rate (lowest σ), implying a possible inception of cavitation.

Page C-39 lists inlet pressures from bollard pull tests of three impellers combined with a 33-inch inlet length and selected nozzle openings. These measured pressures are plotted versus flow rate Q on Page C-40. Also shown is a curve of predicted inlet pressures from the equation for inlet head loss, Page C-15, which is in good agreement with measured pressures.

On the basis of the cavitation criteria examined, it may be tentatively concluded that:

- A 1.0 area ratio impeller shows evidence of cavitation inception at a σ below 2, whereas the two larger area impellers show no such evidence to a σ of about 0.75 at the highest speed tested.

- For cavitation-free performance and highest pump efficiency, the 1.5 area ratio is the choice over the 2.25 area ratio impeller.

Thus, attention in subsequent comparisons will be focused on the 1.5 area ratio impeller.

Calculations of σ, K_T, η_p and J are listed on pages C-41 through C-43 for the 1.5 area ratio impeller/12.25 inch nozzle with three inlet lengths. Charts of the latter three quantities versus σ appear on pages C-44, C-45 and C-46.

While during the bollard tests all three quantities remained essentially constant, showing no sign of degradation with decreasing cavitaion number, the tests at speed showed a reduction in K_T with decreasing σ.

Since it was felt that this might be due to aeration of the flow into the pump when planing at high speeds, a plot of thrust coefficient against volume Froude number was made showing that K_T decreases as F_∇ increases, a result which tends to confirm the presence of ventilation. The data for this plot, shown on page C-49, are tabulated on pages C-47 and C-48.

In any case, for volume Froude numbers corresponding to full scale speeds of 15-25 mph, (hump-cruise) K_T is diminished only slightly to approximately 85 percent of its maximum value. This degradation could be restored by an increase in impeller speed of only 7 or 8 percent.

ESTIMATED PUMP PERFORMANCE CHARACTERISTICS

This section presents a waterjet system design procedure which integrates practical design factors obtained during the July 1984 trials. The initial application is in a design of a modified 14-inch diameter axial flow pump which can be evaluated using the existing testcraft hull and engine. The following particulars and design factors were selected:

- Inlet entrance length of 19.5 inches to minimize overall length of system, since trial results showed no consistent penalty associated with this shortest of the inlet lengths tested.
- A nozzle with a profile as sketched on Page E-1, and an exit diameter of 12 inches.
- 100 percent recovery of dynamic head due to vehicle velocity.
- Limiting values of cavitation index σ ranging from 0.75 to 1.0.

- Propeller characteristic estimates based on a pump efficiency of 0.72 and an impeller advance coefficient of 0.82.

Nozzle configuration and experimental data on nozzle performance were taken from Reference 4. The nozzle profile, Page E-1, causes a contraction of the waterjet beyond the nozzle mouth. This effective waterjet diameter and a head loss coefficient were obtained from the referenced data.

Using the above design particulars, estimates of pump performance characteristics are detailed on Pages D-1 through D-14.

ESTIMATED PERFORMANCE FOR 14 INCH DIAMETER PUMP

Design procedures developed in the previous section have been applied to predict performance of the pump system shown on Page E-1.

The initial step was to develop curves of pump shaft horsepower for nominal values of flow rate and vehicle speed, Page E-4. These curves were then used to obtain flow rate corresponding to nominal values of shaft power and vehicle speed, leading to the construction of curves of jet thrust versus vehicle speed for each nominal shaft horsepower, Page E-9. Nominal values of SHP were chosen to cover the operating range of the existing testcraft engine.

To avoid cavitation, flow rate is limited by a relationship with vehicle speed and a minimum value of cavitation index σ. This equation, developed on Page D-13, was evaluated for $\sigma = 0.75$ and 1.0 to yield cavitation-free flow rate and jet thrust. Curves of jet thrust versus vehicle speed for the two values of cavitation index are superposed on the chart on Page E-9. The two sets of curves show clearly that at top vehicle speed, full engine power should be absorbed by the pump without inception of cavitation.

A chart of predicted overall propulsive coefficient versus SHP, Page E-10 shows that a target of 40 to 45 percent propulsive efficiency can be achieved at a vehicle speed of 20 mph. A chart of pump rpm versus pump SHP predicts that full engine power can be absorbed at top vehicle speed within the engine shaft speed limit.

ESTIMATED PERFORMANCE FOR 16 INCH DIAMETER PUMP

A proposed pump for a high-speed amphibious vehicle is sketched on Page F-1. This 16-inch diameter pump is geometrically similar in certain respects to the 14-inch pump described in the previous section. Inlet dimensions and nozzle exit diameter have been increased by a ratio (16/14), but the overall length of the unit has been changed only two percent. Given the above similarities, performance of the 16-inch pump has been predicted by making the following assumptions.

- Range of craft speed V_o will be identical with that used for 14-inch pump.
- Waterjet velocity V_j and pump head H_p will be independent of pump diameter
- Impeller advance coefficient $J = 0.82$ and pump efficiency $n_p = 0.72$ as for 14-inch pump.
- Flow rate of 16-inch pump $Q_{16} = Q_{14}\ (16/14)^2$

It then follows that.

- Since SHP $\ H_pQ/n_p$, $SHP_{16} = SHP_{14}\ (16/14)^2$
- Since $T_j\ \ Q\ (V_j - V_o)$, $T_{j16} = T_{j14}\ (16/14)^b$
- Since J $\ \ V/ND = (Q/A)/ND$

  or ND $\ \ Q/AJ$

  But Q/AJ has been assumed constant

  Thus ND is constant and $N_{16} = 14N_{14}/16$

These relations were applied to the 14-inch pump predictions to obtain performance estimates for a 16-inch pump. Calculations and charts of performance characteristics are detailed on Pages F-2 through F-9.

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1. Roper, John K. "Development of Waterjet Propulsion Unit", Davidson Laboratory Report 2328, March 1982.

2. Numata, E., "Performance Trial of a Manned Waterjet Testcraft", Davidson Laboratory Report 2390, March 1984.

3. Marks' Standard Handbook for Mechanical Engineers (8th. Ed.), McGraw-Hill Book Company.

4. Ellis, W.E. and Sobolewski, A.D. "Propulsion Experiment with a Planing Hull Having Two Flush Inlet Configurations" DTNSRDC/SPD-0786-01, March 1978.

APPENDIX A

NOMENCLATURE

A_I	=	INLET AREA (JUST AHEAD OF PROP.)	FT^2
A_J	=	JET AREA (AT MINIMUM JET DIAM.)	FT^2
A_P	=	FLOW AREA AT PROP. $(= A_I)$	FT^2
APSI	=	MEASURED PRESSURE IN INLET (JUST AHEAD OF PROP.)	PSIG
D	=	PROP. DIAM.	FT
$H_{ATM.}$	=	HEAD DUE TO ATMOSPHERIC PRESSURE	FT
H_{I_S}	=	INLET STATIC HEAD	FT
H_O	=	HEAD RECOVERED FROM FREE STREAM	FT
H_P	=	PUMP HEAD	FT
$H_{P_{CAV}}$	=	PUMP HEAD AT CAVITATION LIMIT	FT
$H_{VAP.}$	=	HEAD CORRESPONDING TO VAPOR PRESSURE	FT
HL_C	=	CASING HEAD LOSS	FT.
HL_I	=	INLET HEAD LOSS	FT
HL_J	=	NOZZLE HEAD LOSS	FT
HL_M	=	HEAD LOSS DUE TO MEASURING EQUIP.	FT.
J	=	PROP. ADVANCE COEF. $= \dfrac{V_C}{nD}$	
K_C	=	CAVITATION INDEX $= \dfrac{H_P/PAR}{H_{I_S} - H_{VAP}}$	
K_T	=	PROP. THRUST COEF. $= \dfrac{T}{\rho n^2 D^4}$	
n	=	PROP. SPEED	RPS
N	=	PROP SPEED	RPM
OPC	=	OVERALL PROPULSIVE COEF. $= \dfrac{T_T V_O}{550 SHP}$	
PAR	=	PROJECTED AREA RATIO OF PROP.	
Q	=	FLOW RATE	FT^3/SEC
R_M	=	RESISTANCE OF MEASURING EQUIP.	—

NOMENCLATURE (CONT.)

RPR	=	RAM PRESSURE RECOVERY RATIO = $\dfrac{H_0}{V_0^2/2g}$	
S	=	SUCTION SPECIFIC SPEED = $21.19\,\dfrac{(Q)^{1/2}}{(H_{I_0} - H_{VAP})^{3/4}}$	
SHP	=	POWER TO PUMP	HP
T_B	=	BOLLARD PULL	#
T_J	=	JET THRUST	#
T_S	=	SHAFT (PROP.) THRUST	#
V_I	=	INLET VELOCITY (JUST AHEAD OF PROP)	FT/SEC
V_J	=	JET VELOCITY (AT MINIMUM JET DIAM)	FT/SEC
V_{MPH}	=	CRAFT SPEED	MPH
V_0	=	CRAFT SPEED	FT/SEC
V_P	=	VELOCITY AT PROP. ($= V_I$)	FT/SEC
η_P	=	PUMP EFFICIENCY = $\dfrac{\rho g H_P Q}{550\,SHP}$	

APPENDIX B

PREDICTED INLET LOSSES

SUMMARY

	33" INLET	23" INLET	19.5" INLET
ENTRANCE	.8669	1.7856	2.4820
DUCT FRICTION + BEND	1.8365	2.6055	3.3875
SHAFT	.3232	.7699	1.1749
TRANSITION	1.4691	1.4691	1.4691
BEARING TUBE (FRICTION)	.0752	.0752	.0752
BEARING TUBE (FRONTAL)	.3247	.3247	.3247
STRUTS (PROFILE)	.1866	.1866	.1866
STRUTS (INTERFERENCE)	.0093	.0093	.0093
HL_I	5.0915	7.2259	9.1093
$k = \frac{HL_I}{Q^2_{NOM}} =$	.002037	.002890	.003755

PREDICTED INLET LOSSES

ENTRANCE (33" INLET)

Q = NOM. FLOW RATE = 50 FT^3/SEC

A = ENTRANCE AREA = $\frac{(14)(33)}{144}$ = 3.208 FT^2

V = ENTRANCE VELOCITY = $\frac{Q}{A} = \frac{50}{3.208}$ = 15.58 FT/SEC

K = LOSS COEF. = .23 (CRANE, 'SLIGHTLY ROUNDED' ENTRANCE)

$HL = K\frac{V^2}{2g} = \frac{(.23)(15.58)^2}{2(32.2)}$ = .8669'

ENTRANCE (23" INLET)

Q = 50 FT^3/SEC

$A = \frac{(14)(23)}{144}$ = 2.2361 FT^2

$V = \frac{Q}{A} = \frac{50}{2.2361}$ = 22.36 FT/SEC

K = .23

$HL = K\frac{V^2}{2g} = \frac{(.23)(22.36)^2}{2(32.2)}$ = 1.7856'

ENTRANCE (19.5" INLET)

Q = 50 FT^3/SEC

$A = \frac{(14)(19.5)}{144}$ = 1.8958 FT^2

$V = \frac{Q}{A} = \frac{50}{1.8958}$ = 26.37 FT/SEC

K = .23

$HL = K\frac{V^2}{2g} = \frac{(.23)(26.37)^2}{2(32.2)}$ = 2.482

PREDICTED INLET LOSSES

DUCT FRICTION & BEND (33" INLET)

Q = NOM. FLOW RATE = 50 FT³/SEC

A = DUCT AREA $= \frac{(14)(17)}{144} = 1.6528$ FT²

V = DUCT VELOCITY $= Q/A = \frac{50}{1.6528} = 30.25$ FT/SEC.

d_e = EQUIV. DUCT DIAM. $= \frac{4A}{2\left(\frac{14+17}{12}\right)} = \frac{4(1.6528)(12)}{2(14+17)} = 1.2796'$

$R_e = \frac{V d_e}{1.24 \times 10^{-5}} = \frac{(30.25)(1.2796)}{1.24 \times 10^{-5}} = 3.12 \times 10^6$

e = ROUGHNESS = $.000005'$ (CRANE – SIM. TO DRAWN TUBING)

$e/d_e = .000005/1.2796 = .0000039$

f = FRICTION FACTOR $= .0097$ (CRANE)

L_D = DUCT LENGTH $= \sqrt{(16.?)^2 + (8.?)^2} = 14.14'' = 1.18'$

L_B = EQUIV. LENGTH OF BEND $= \left.\frac{L}{D}\right)_B d_e \left(\frac{\alpha}{90}\right) = (36)(1.2796)\left(\frac{31.01}{90}\right) = 15.87'$

L = TOT EQUIV. LENGTH $= L_D + L_B = 1.18 + 15.87 = 17.05'$

$HL = f\left(\frac{L}{D_e}\right)\frac{V^2}{2g} = (.0097)\left(\frac{17.05}{1.2796}\right)\frac{(30.25)^2}{2(32.2)} = 1.8365'$

PREDICTED INLET LOSSES

DUCT FRICTION + BEND (23" INLET)

$Q = 50 \text{ FT}^3/\text{SEC}$

$A = \dfrac{(14)(17)}{144} = 1.6528 \text{ FT}^2$

$V = Q/A = 50/1.6528 = 30.25 \text{ FT/SEC}$

$d_e = \dfrac{4A}{2\left(\frac{14+17}{12}\right)} = \dfrac{4(1.6528)(12)}{2(14+17)} = 1.2796'$

$R_e = \dfrac{V d_e}{1.24 \times 10^{-5}} = \dfrac{(30.25)(1.2796)}{1.24 \times 10^{-5}} = 3.12 \times 10^6$

$e = .000005'$

$e/d_e = .000005/1.2796 = .0000039$

$f = .0097$

$L_D = \sqrt{(11.5)^2 - (8.5)^2} = 7.75 = .65'$

$L_B = \left(\dfrac{L}{D}\right)_B d_e \left(\dfrac{K}{90}\right) = (36)(1.2796)\left(\dfrac{46}{90}\right) = 23.54'$

$L = L_D + L_B = .65 + 23.54 = 24.19'$

$HL = f\left(\dfrac{L}{d_e}\right)\dfrac{V^2}{2g} = (.0097)\left(\dfrac{24.19}{1.2796}\right)\dfrac{(30.25)^2}{2(32.2)} = 2.6055'$

PREDICTED INLET LOSSES

DUCT FRICTION + BEND (19.5" INLET)

$Q = 50 \text{ FT}^3/\text{SEC}$

$A = \frac{(14)(17)}{144} = 1.6528 \text{ FT}^2$

$V = Q/A = \frac{50}{1.6528} = 30.25 \text{ FT/SEC.}$

$d_e = \frac{4A}{2\left(\frac{14+17}{12}\right)} = \frac{4(1.6528)(12)}{2(14+17)} = 1.2796'$

$R_e = \frac{V d_e}{1.24 \times 10^{-5}} = \frac{(30.25)(1.2796)}{1.24 \times 10^{-5}} = 3.12 \times 10^6$

$e = .000005$

$e/d_e = .000005/1.2796 = .0000039$

$f = .0097$

$L_D = \sqrt{(9.75)^2 - (8.5)^2} = 4.78'' = .40'$

$L_B = \left(\frac{L}{D}\right)_B d_e \left(\frac{\alpha}{90}\right) = (36)(1.2796)\left(\frac{60.67}{90}\right) = 31.05'$

$L = L_D + L_B = .40 + 31.05 = 31.45'$

$H_L = f\left(\frac{L}{d_e}\right)\frac{V^2}{2g} = (.0097)\left(\frac{31.45}{1.2796}\right)\frac{(30.25)^2}{2(32.2)} = 3.3875'$

PREDICTED INLET LOSSES

SHAFT (33" INLET)

Q = NOM. FLOW RATE = 50 FT^3/SEC

A = DUCT AREA = 1.6528 FT^2

V = DUCT VELOCITY = Q/A = 50/1.6528 = 30.25 FT/SEC

C_D = DRAG COEF. = $1.1 \sin^3 \alpha$ = $1.1 \sin^3 31.01$ = .1504

ℓ = SHAFT LENGTH = 2'

d = SHAFT DIAM. = 1.50" = .125'

D = SHAFT DRAG = $C_D \frac{\rho}{2} V^2 \ell d = (.1504)\left(\frac{1.94}{2}\right)(30.25)^2(.125) = 33.37^{\#}$

$HL = \frac{D}{\rho g A} = \frac{33.37}{(1.94)(32.2)(1.6528)} = .3232'$

SHAFT (23" INLET)

Q = 50 FT^3/SEC.

A = 1.6528 FT^2

V = Q/A = 50/1.6528 = 30.25 FT/SEC

C_D = $1.1 \sin^3 \alpha$ = $1.1 \sin^3 46$ = .4094

ℓ = 1.75'

d = .125'

$D = C_D \left(\frac{\rho}{2}\right) V^2 \ell d = (.4094)\left(\frac{1.94}{2}\right)(30.25)^2(1.75)(.125) = 79.49^{\#}$

$HL = \frac{D}{\rho g A} = \frac{79.49}{(1.94)(32.2)(1.6528)} = .7699'$

PREDICTED INLET LOSSES

SHEET (19.5" INLET)

$Q = 50\ ft^3/sec$

$A = 1.6528\ ft^2$

$V = Q/A = 50/1.6528 = 30.25\ ft/sec$

$C_D = 1.1 \sin^3\alpha = 1.1 \sin^3 60.67 = .7269$

$l = 1.5'$

$d = .125'$

$D = C_D \frac{\rho}{2} V^2 l d = (.7269)\left(\frac{1.94}{2}\right)(30.25)^2(1.50)(.125) = 121.31^{\#}$

$HL = \frac{D}{\rho g A} = \frac{121.31}{(1.94)(32.2)(1.6528)} = 1.1749'$

PREDICTED INLET LOSSES

TRANSITION

Q = NOM. FLOW RATE = 50 FT^3/SEC

A = AREA AT PROP. (SMALL END OF TRANSITION) = $\frac{(.96)(.5)(14.12)^2}{144}$ = 1.0434 FT^2

V = VELOCITY AT PROP = Q/A = 50/1.0434 = 47.92 FT/SEC

C_D = DISCHARGE COEF. = .98

K = LOSS COEF. = $\frac{1}{C_D^2} - 1 = \frac{1}{(.98)^2} - 1$ = .0412

$HL = K\frac{V^2}{2g} = \frac{(.0412)(47.92)^2}{2(32.2)}$ = 1.4691'

BEARING TUBE (FRICTION)

V = VELOCITY AT PROP = 47.92 FT/SEC

ℓ = TUBE LENGTH = .67'

$Re = \frac{V\ell}{1.24 \times 10^{-5}} = \frac{(47.92)(.67)}{1.24 \times 10^{-5}}$ = 2.59×10^6

C_f = .00366

S = TUBE WETTED SURF. = $.67 \times \frac{2.80}{12}$ = .4911 FT^2

D = TUBE DRAG = $(C_f + .0008) S \frac{\rho}{2} V^2$ = [illegible] $(\frac{1.94}{2})(47.92)^2$ = 4.90#

$HL = \frac{D}{\rho g A} = \frac{4.90}{(1.94)(32.2)(1.0434)}$ = .0752'

BEARING TUBE (FRONTAL)

A_o = FRONTAL AREA = [illegible] = .0095 FT^2

V = 47.92 FT/SEC

C_D = DRAG COEF = 1

D = FRONTAL DRAG = $C_D A_o \frac{\rho}{2} V^2$ = [illegible] = 21.16#

$HL = \frac{D}{\rho g A} = \frac{21.16}{(1.94)(32.2)(1.0434)}$ = .3247'

PREDICTED INLET LOSSES

STRUTS (PROFILE)

Q = NOM. FLOW RATE = 50 FT^3/SEC.

A = AREA AT PROP. = 1.0434 FT^2

V = VELOCITY AT PROP. = Q/A = 50/1.0434 = 47.92 FT/SEC.

c = STRUT CHORD = 3" = .25'

$$R_e = \frac{Vc}{1.24 \times 10^{-5}} = \frac{(47.92)(.25)}{1.24 \times 10^{-5}} = 9.66 \times 10^5$$

C_f = .00439

t/c = .3125/3 = .1042

$C_D = 2(C_f + .0008)(1 + 1.2\,t/c) = 2(.00439 + .0008)(1 + 1.2 \times .1042) = .0117$

S = STRUT PLANFORM AREA = $2\dfrac{(14 - 2.80)(3)}{144}$ = .4667 FT^2

D = STRUT DRAG = $C_D S \frac{\rho}{2} V^2 = (.0117)(.4667)(\frac{1.94}{2})(47.92)^2 = 12.16$#

$$HL = \frac{D}{\rho g A} = \frac{12.16}{(1.94)(32.2)(1.0434)} = .1866'$$

STRUTS (INTERFERENCE)

A = 1.0434 FT^2

V = 47.92 FT/SEC

t = .3.25/12 = .0260'

t/c = .1042

$$C_D = .75\,t/c - \frac{.0003}{(t/c)^2} = (.75)(.1042) - \frac{.0003}{(.1042)^2} = .0505$$

D = INTERFERENCE DRAG = $8 C_D t^2 \frac{\rho}{2} V^2 = 8(.0505)(.026)^2(\frac{1.94}{2})(47.92)^2 = .6083$

$$HL = \frac{D}{\rho g A} = \frac{.6083}{(1.94)(32.2)(1.0434)} = .0093'$$

PREDICTED CASING LOSS

CASING

Q = NOMINAL FLOW RATE = 50 FT^3/SEC

A = CASING AREA = $(.785)\left(\frac{14.12}{12}\right)^2$ = 1.087 FT^2

V = CASING VELOCITY = Q/A = 50/1.087 = 46.00 FT/SEC

d = CASING DIAM = 14.12" = 1.1767'

$R_e = \frac{Vd}{1.24 \times 10^{-5}} = \frac{(46)(1.1767)}{1.24 \times 10^{-5}} = 4.37 \times 10^6$

e = ROUGHNESS = .000005'

e/d = .000005/1.1767 = .0000042

f = FRICTION FACTOR = .0095

L = CASING LENGTH = 1.33'

$HL = f\left(\frac{L}{d}\right)\frac{V^2}{2g} = (.0095)\left(\frac{1.33}{1.1767}\right)\frac{(46)^2}{2(32.2)} = .3537'$

$k = \frac{HL}{Q_{nom}^2} = \frac{.3537}{(50)^2} = .000141$

$HL_c = .000141\ Q^2$

PREDICTED NOZZLE LOSSES

10.5" DIAM. NOZZLE

$$HL = \frac{V^2}{2g}(1+K)$$

$$\frac{V^2}{2g} = \left(\frac{Q}{A}\right)^2 \frac{1}{2g}$$

$$A = (.785)(10.5)^2/144 = .6010 \text{ ft}^2$$

$$\frac{V^2}{2g} = \frac{Q^2}{(.600)^2(1)(32.2)} = .0430\,Q^2$$

$$1+K = \frac{1}{C_D^2}$$

$$C_D = .97$$ (FAN ENG. EQ. 38)

$$1+K = \frac{1}{(.97)^2} = 1.0628$$

$$HL = .0430Q^2(1.0628) = .045690\,Q^2$$

12.25" DIAM. NOZZLE

$$HL = \frac{V^2}{2g}(1+K)$$

$$\frac{V^2}{2g} = \left(\frac{Q}{A}\right)^2 \frac{1}{2g}$$

$$A = (.785)(12.25)^2/144 = .8180 \text{ ft}^2$$

$$\frac{V^2}{2g} = \frac{Q^2}{(.8180)^2(1)(32.2)} = .0232\,Q^2$$

$$1+K = \frac{1}{C_D^2}$$

$$C_D = .97$$

$$1+K = \frac{1}{(.97)^2} = 1.0628$$

$$HL = .0232\,Q^2(1.0628) = .024664\,Q^2$$

PREDICTED NOZZLE LOSSES

14.00" NOZZLE (NO NOZZLE)

$$HL = \frac{V^2}{2g}(1+K)$$

$$\frac{V^2}{2g} = \left(\frac{Q}{A}\right)^2 \frac{1}{2g}$$

$$A = (.785)(14.12)^2/144 = 1.087\ \text{ft}^2$$

$$\frac{V^2}{2g} = \frac{Q^2}{(1.087)^2(2)(32.2)} = .013142Q^2$$

$$K = 0$$

$$HL = .0131Q^2(1+0) = .013142Q^2$$

ESTIMATED MEASUREMENT LOSSES (12.25" NOZZLE)

RACK

Q = NOM. FLOW RATE 50 FT³/SEC

A = NOZZLE EXIT AREA = $\frac{(.785)(12.25)^2}{144}$ = .8180 FT²

V = Q/A = 50/.818 = 61.12 FT/SEC

ℓ = RACK LENGTH = 12.25' = 1.021

d = RACK LEADING EDGE DIAM. = .75" = .0625'

C_D = DRAG COEF = 1.1

$R = C_D \ell d \frac{\rho}{2} V^2 = (1.1)(1.021)(.0625)(\frac{1.94}{2})(61.12)^2 = 254.35$#

PITOT TUBES

ℓ = TUBE LENGTH = 2(1.75+2.75+4.2+5.1+5.7+6.0)+1(6.1+3.75) = 59.85" = 4.99'

d = TUBE DIAM = 3/32 = .00783'

C_D = 1.1

$R = C_D \ell d \frac{\rho}{2} V^2 = (1.1)(4.99)(.00783)(\frac{1.94}{2})(61.12)^2 = 155.40$#

TOTAL

R_M = 254.35 + 155.40 = 409.75#

$H_{LM} = \frac{R_M}{\rho g A} = \frac{409.75}{(1.94)(32.2)(.818)}$ = 8.02'

$k = \frac{H_L}{Q^2} = \frac{8.02}{(50)^2}$ = .003207

$K = \frac{D}{Q^2} = \frac{409.75}{(50)^2}$ = .1639

H_{LM} = .003207 Q^2

PREDICTED INLET PRESSURE RECOVERY

$$H_o = RPR \frac{V_o^2}{2g}$$

$$RPR = 1.00$$

$$H_o = (1.00)\frac{V_o^2}{2(32.2)} = .0155 V_o^2$$

PREDICTED PUMP HEAD REQUIRED

$$H_P = HL_I + HL_C + HL_J + HL_M - H_O$$

Noz.	Inlet	HL_I	HL_C	HL_J	HL_M	H_O	H_P
14.00	19.5	$.003755Q^2$	$.000141Q^2$	$.013142Q^2$	$.003207Q^2$	$.0155V_o^2$	$.020245Q^2 - .0155V_o^2$
	23	$.002890Q^2$					$.019380Q^2 - .0155V_o^2$
	33	$.002037Q^2$					$.018527Q^2 - .0155V_o^2$
12.25	19.5	$.003755Q^2$		$.024664Q^2$			$.031763Q^2 - .0155V_o^2$
	23	$.002890Q^2$					$.030761Q^2 - .0155V_o^2$
	33	$.002037Q^2$					$.030049Q^2 - .0155V_o^2$
10.50	19.5	$.003755Q^2$		$.045690Q^2$			$.052793Q^2 - .0155V_o^2$
	23	$.002890Q^2$					$.051928Q^2 - .0155V_o^2$
	33	$.002037Q^2$					$.051075Q^2 - .0155V_o^2$

PREDICTED SHP REQUIRED

$$SHP = \frac{H_p Q \rho g}{550 \eta_p}$$

$$\eta_p = .72$$

$$SHP = H_p Q \frac{(1.94)(32.2)}{(550)(.72)} = .1577 H_p Q$$

APPENDIX C

Performance Data Summary

1.5 Prop / 10.25" Nozl / 23 [illegible]   O

Run #	V_{MPH}	T_J	SHP	[illegible]	J	η_P	Q
201	4.95	35[illegible]	13	[illegible]	.59	.03	16.06
202	[illegible]	923	103	[illegible]	.90	.25	32.9[illegible]
203	25.3	905	125	.330	.90	.27	40.3[illegible]
204	25.30	939	154	.381	.90	.33	40.27
205	20.23	1054	98	[illegible]	.63	.31	42.05
206	13.[illegible]	955	24	[illegible]	.61	.31	23.48
207	10.93	1125	83	[illegible]	.89	.33	29.3[illegible]
208	8.49	992	51	.45[illegible]	.63	.30	26.3[illegible]
209	5.40	1035	51	.454	.69	.36	[illegible]
[illegible]	3.30	32[illegible]	26	.454	[illegible]	.04	[illegible]
211	[illegible].33	622	2[illegible]	.455	.59	.43	20.77
212	[illegible]	154	3	0	.20	.23	8.39
213	0	[illegible]	[illegible]	0	[illegible]	.22	14.06
214	0	943	40	0	.33	.23	20.04
[illegible]	0	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]
[illegible]	0	226[illegible]	[illegible]	0	.29	[illegible]	31.10
[illegible]	0	295[illegible]	21[illegible]	0	.31	.23	35.36
218	[illegible]	[illegible]	[illegible]	.403	.68	.35	[illegible]
[illegible]	[illegible]	990	141	[illegible]	.88	[illegible]	[illegible]
220	[illegible]	1001	[illegible]	.340	.80	[illegible]	[illegible]

PERFORMANCE DATA SUMMARY

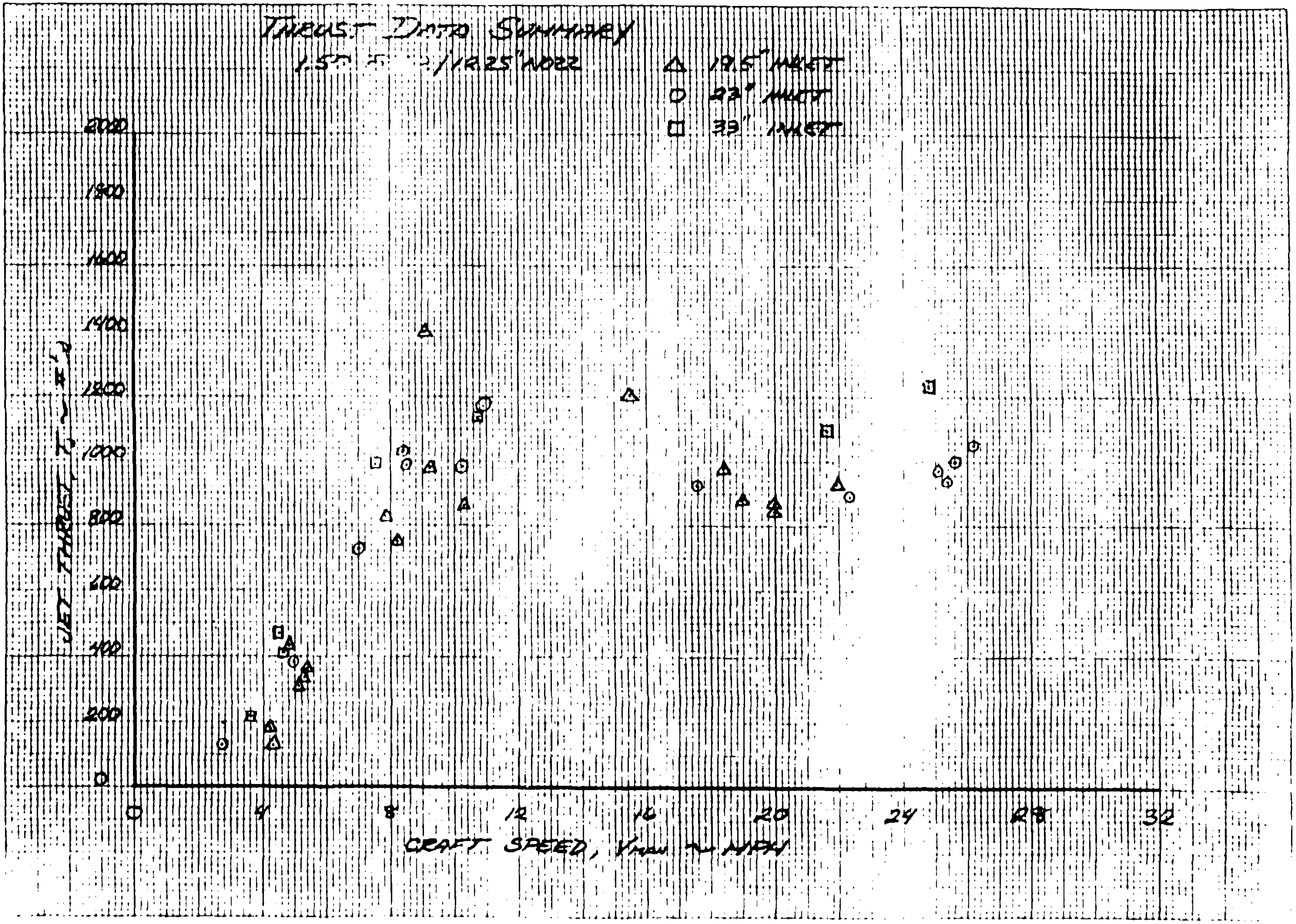
1.50 PROP / 12.25 / NOZ. / 19.5" INLET △

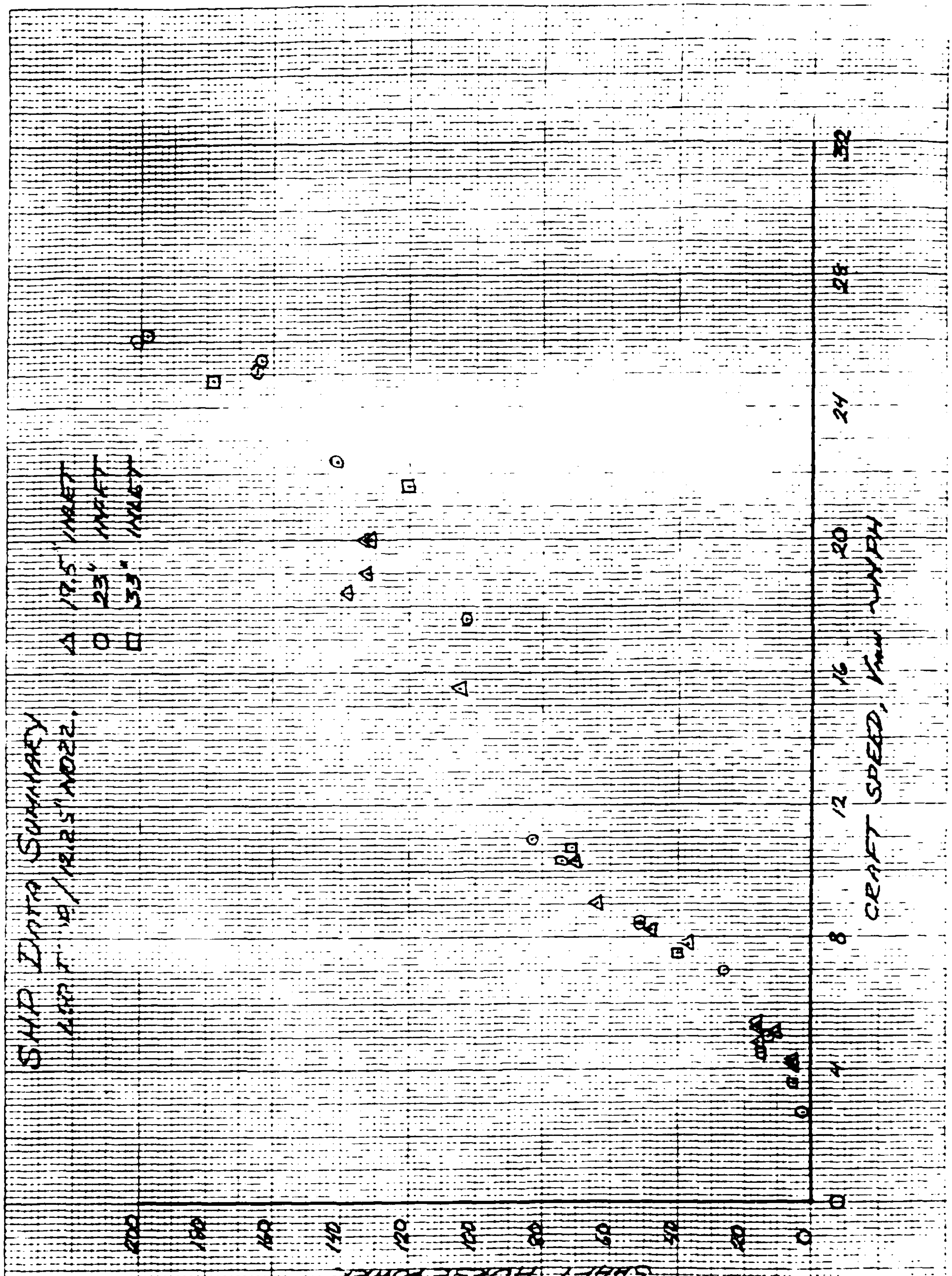
RUN #	VMPH	T_J	SHP	[illegible]	[illegible]	[illegible]	[illegible]
221	4.76	[illegible]	[illegible]	[illegible]	.80	.76	[illegible]
222	5.42	[illegible]	16	.327	.84	.83	[illegible]
223	5.73	336	16	.192	.83	.79	[illegible]
224	18.78	684	13[illegible]	.310	.86	.74	33.81
225	20.03	843	131	.345	.86	.75	34.38
226	19.[illegible]	[illegible]	30	.332	.84	.73	26.18
227	6.[illegible]	[illegible]	38	[illegible]	.87	.71	23.39
228	0	308	6	0	.85	.62	11.41
229	0	624	7	0	.84	.70	16.[illegible]
230	0	1223	47	0	.88	.75	22.[illegible]
231	0	1902	70	0	.81	.7	26.34
232	0	2354	131	0	.8[illegible]	.69	31.[illegible]
232	0	2305	13[illegible]	0	.82	.70	31.[illegible]
233	0	3120	221	0	.83	.73	36.35
234	4.22	[illegible]	5	.397	.85	.77	11.71
235	4.55	437	16	.361	.92	.84	16.82
236	15.42	[illegible]	138	.350	.86	.74	34.20
237	9.76	1398	2	α	α	α	[illegible]
238	[illegible]	[illegible]	192	289	.72	.63	36.[illegible]
239	15.5[illegible]	1207	125	[illegible]	.9[illegible]	.70	33.[illegible]
240	20.25	[illegible]	[illegible]	.34[illegible]	.87	.71	34.[illegible]
241	2.[illegible]	[illegible]	[illegible]	.33[illegible]	.86	.73	[illegible]
242	7.81	[illegible]	[illegible]	.463	.90	[illegible]	[illegible]
243	[illegible]	[illegible]	[illegible]	[illegible]	.81	[illegible]	14.99

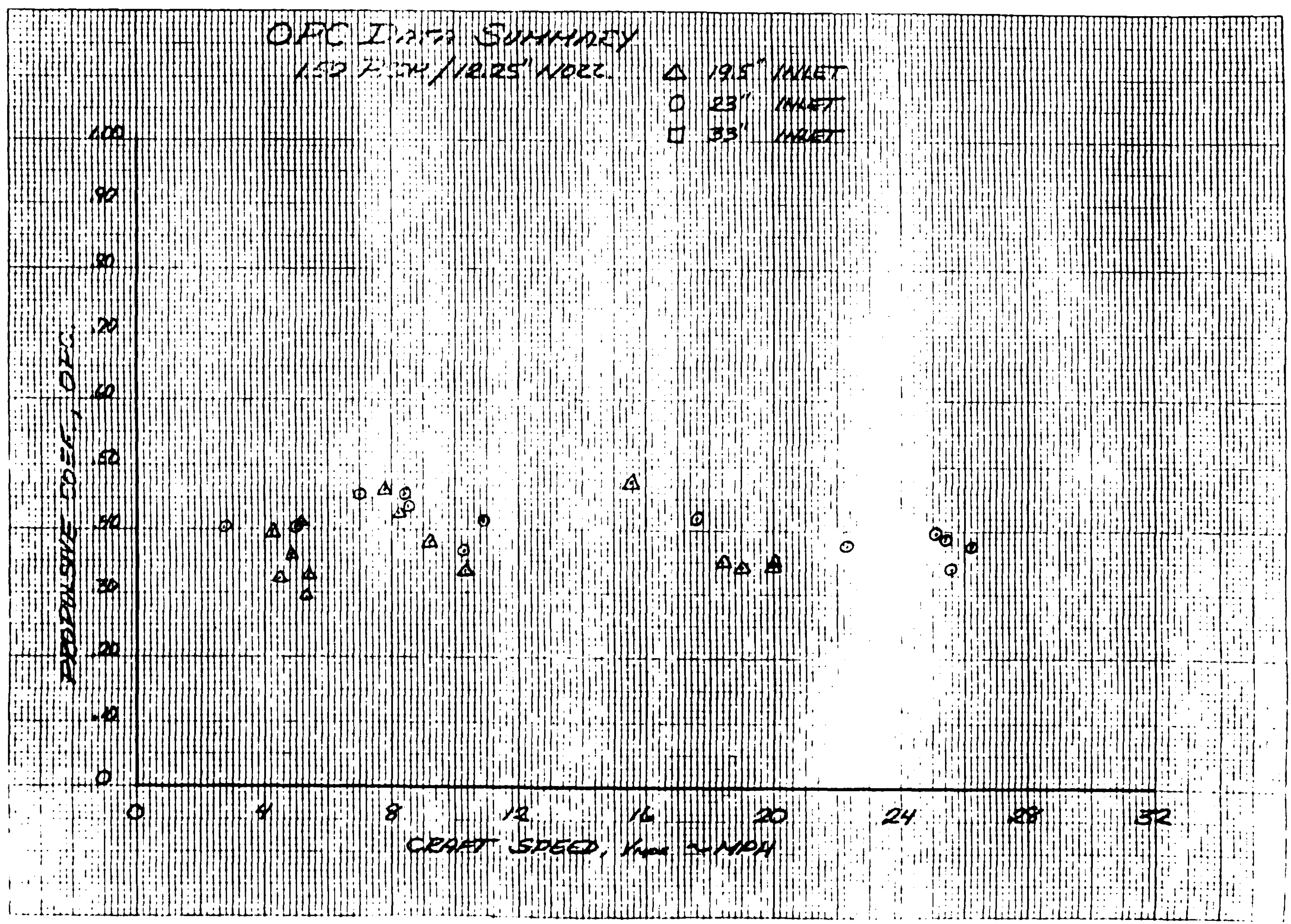
PERFORMANCE DATA SUMMARY

1.50 PROP / 12.25 NOZZ / 33 INLET ☐

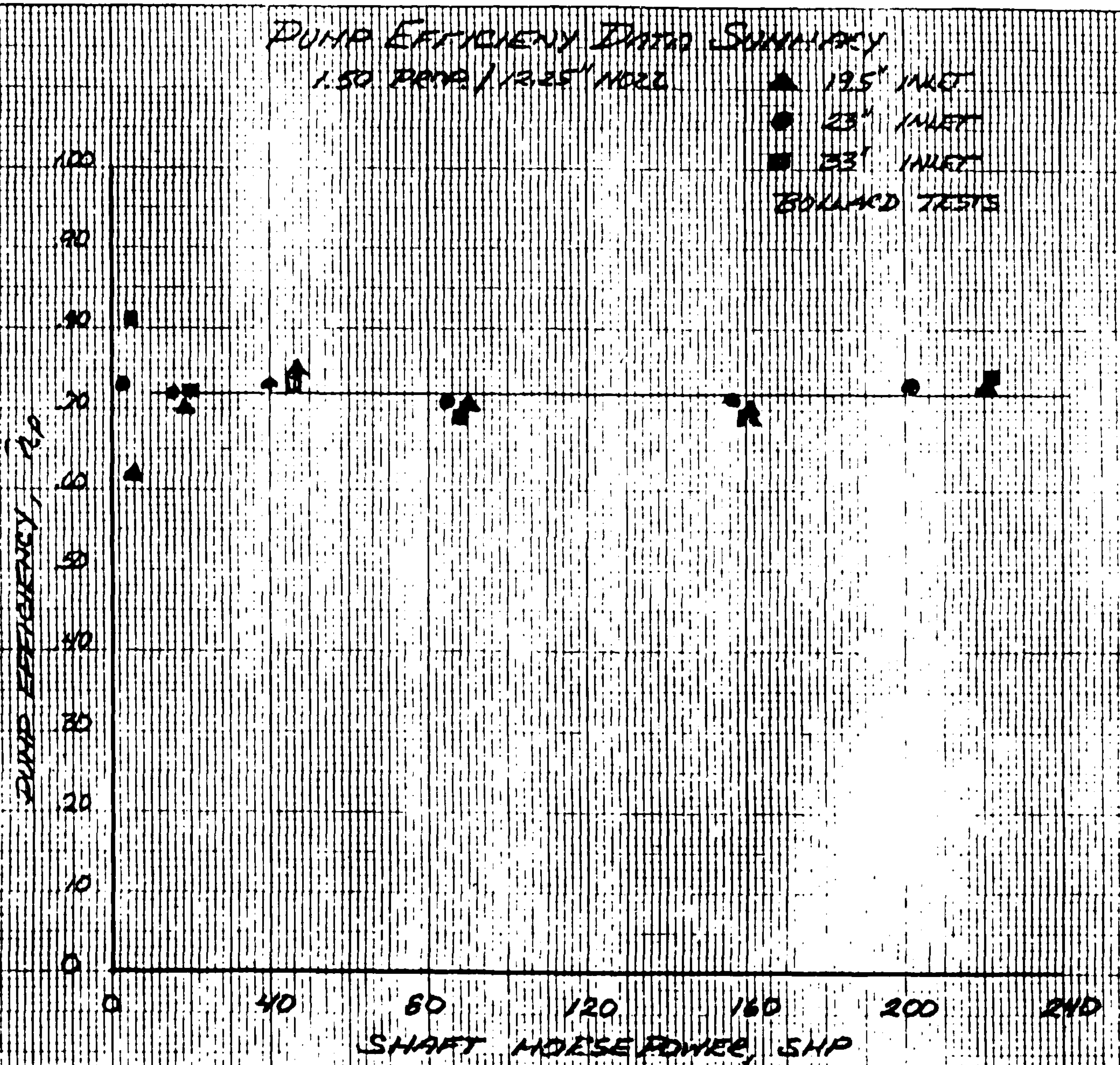
RUN #	V[illegible]	TJ	SHP	SPC	J	η_p	Q
241	3.[illegible]	2[illegible]	5	.303	.59	.28	12.02
245	4.35	[illegible]	5	.372	.73	.54	12.35
246	4.55	4[illegible]	12	.322	.82	.59	16.23
247	21.59	1092	120	.355	.74	.81	38.36
248	24.81	1232	155	.120	.92	.76	42.12
249	10.31	1135	[illegible]	.477	.92	.79	29.[illegible]
250	9.50	956	40	.391	.92	.70	25.43
251	0	274	5	0	.60	.81	10.33
252	0	610	20	0	.52	.32	16.03
253	0	1041	46	0	.51	.33	21.00
253	0	1136	[illegible]	0	[illegible]	.35	2[illegible]
254	0	[illegible]	88	0	.56	.49	24.96
255	0	2310	150	0	.60	.59	31.28
256	0	3230	222	0	.51	.74	36.97

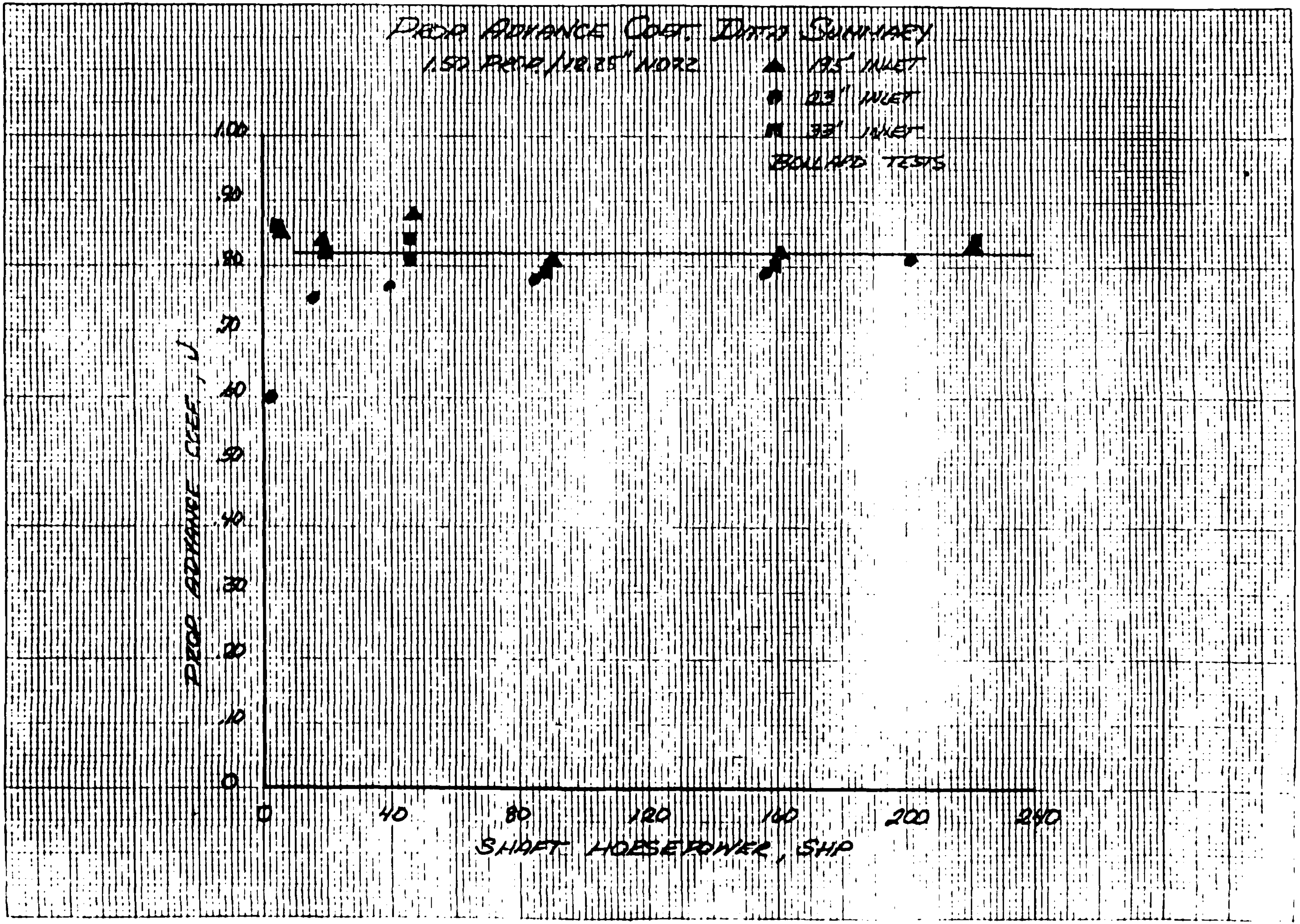

THRUST DATA SUMMARY
19.5" INLET
23" INLET
33" INLET
JET THRUST, T ~ #
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
4
8
12
16
20
24
28
32
CRAFT SPEED, V ~ MPH


SHP DATA SUMMARY
LCRT 10/12.25" NOZZ.
△ 17.5" INLET
○ 23" INLET
□ 33" INLET
SHAFT HORSE POWER
0
20
40
60
80
100
120
140
160
180
200
CRAFT SPEED, V_m MPH
0
4
8
12
16
20
24
28
32



OPC I DATA SUMMARY
/12.25' NOZZ.
△ 19.5" INLET
○ 23" INLET
□ 33" INLET
PROPULSIVE COEF., OPC
100
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
0
4
8
12
16
20
24
28
32
CRAFT SPEED, V_{MPH} ~ MPH


PUMP EFFICIENCY DATA SUMMARY
1.50 PROP / 12.25" NOZZ
19.5" INLET
23" INLET
33" INLET
BOLLARD TESTS
PUMP EFFICIENCY, η_P
SHAFT HORSEPOWER, SHP
0
40
80
120
160
200
240
10
20
30
40
50
60
70
80
90
100


PROP ADVANCE COEF. DATA SUMMARY
1.50 PROP/12.25" HORZ
19.5" INLET
23" INLET
33" INLET
BOLLARD TESTS
PROP ADVANCE COEF, J
SHAFT HORSEPOWER, SHP

STATIC THRUST COMPARISON

1.50 PROP.

$T_B = T_J - R_M$

$T_J = \rho Q (V_J - V_0)$

$V_J = \dfrac{Q}{A_J} = \dfrac{Q}{.8180} = 1.2224\, Q$

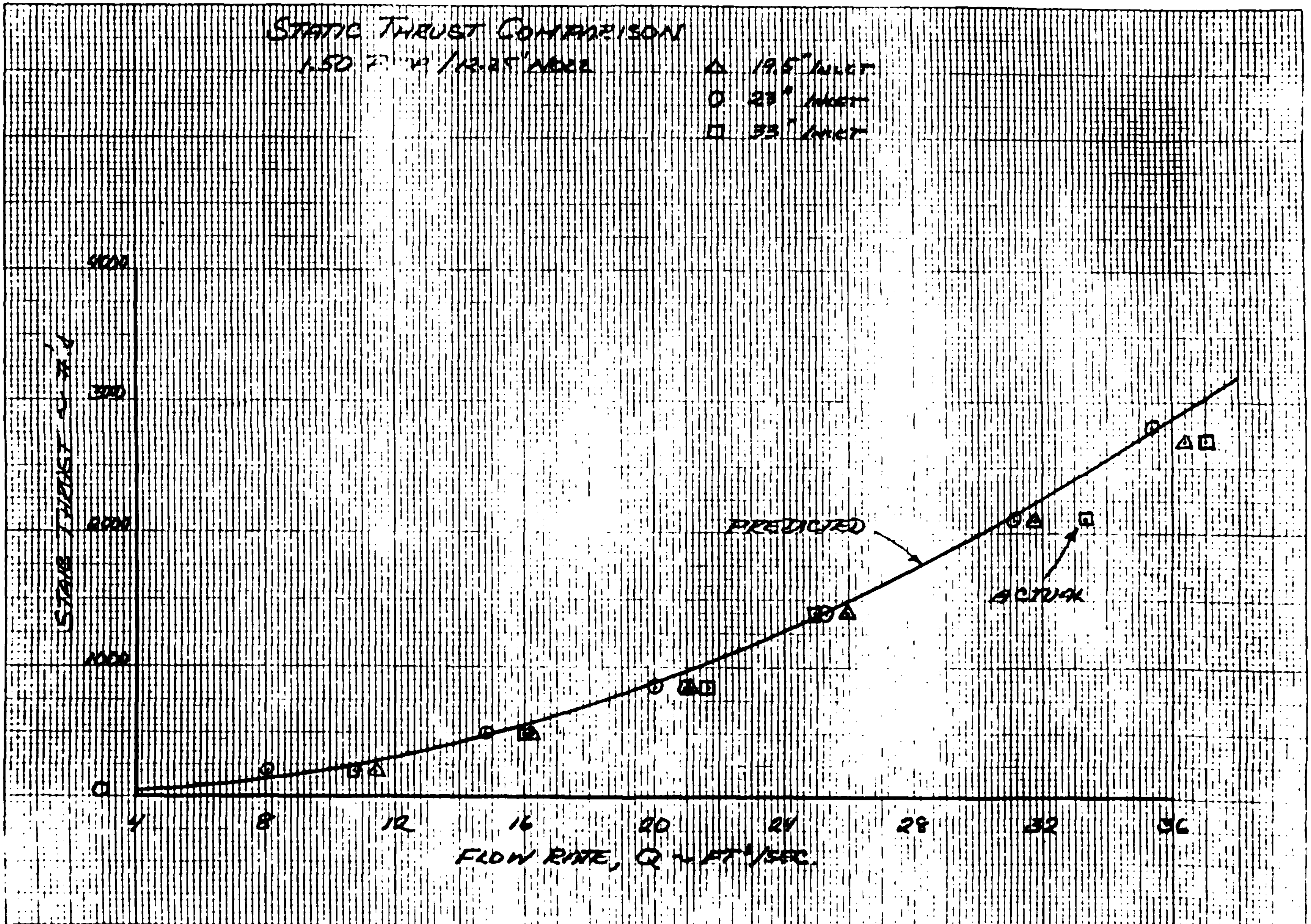
$V_0 = 0$

$T_J = 1.94\, Q (1.2224\, Q - 0) = 2.3715\, Q^2$

$R_M = .1639\, Q^2$

$T_B = 2.3715\, Q^2 - .1639\, Q^2 = 2.2076\, Q^2$ ([illegible])

Run #	Nozz	Inlet	Q	Pred. T_B	Act. T_B
212	12.25'	23"	8.00	144	200
213		⊙	14.06	481	500
214			20.04	887	850
215			25.30	1413	1400
216			31.10	2135	2200
217			35.38	2763	2800
228	12.25'	19.5"	11.41	287	200
229		△	16.25	583	500
[illegible]			22.76	1144	850
[illegible]			26.04	1497	1400
[illegible]			31.00	2228	2100
[illegible]			31.65	2211	2100
233			36.35	2917	2700
251	12.25'	33"	10.00	256	200
252		◻	16.07	570	500
253			21.00	974	850
253			21.66	1036	850
254			24.96	1375	1400
255			[illegible]	2160	2100
256			36.99	3021	2700



STATIC THRUST COMPARISON
19.5" INLET
23" INLET
33" INLET
PREDICTED
ACTUAL
0
1000
2000
3000
4000
4
8
12
16
20
24
28
32
36
FLOW RATE, Q ~ FT³/SEC

INLET LOSS COMPARISON (BOLLARD TEST)

1.50 PROD. / 12.25 NOZZ / 23" INLET

$$H_{I_S} = H_0 - HL_I - \frac{V_I^2}{2g}$$

$$H_0 = 0$$

$$HL_I \quad .00287\, Q^2$$

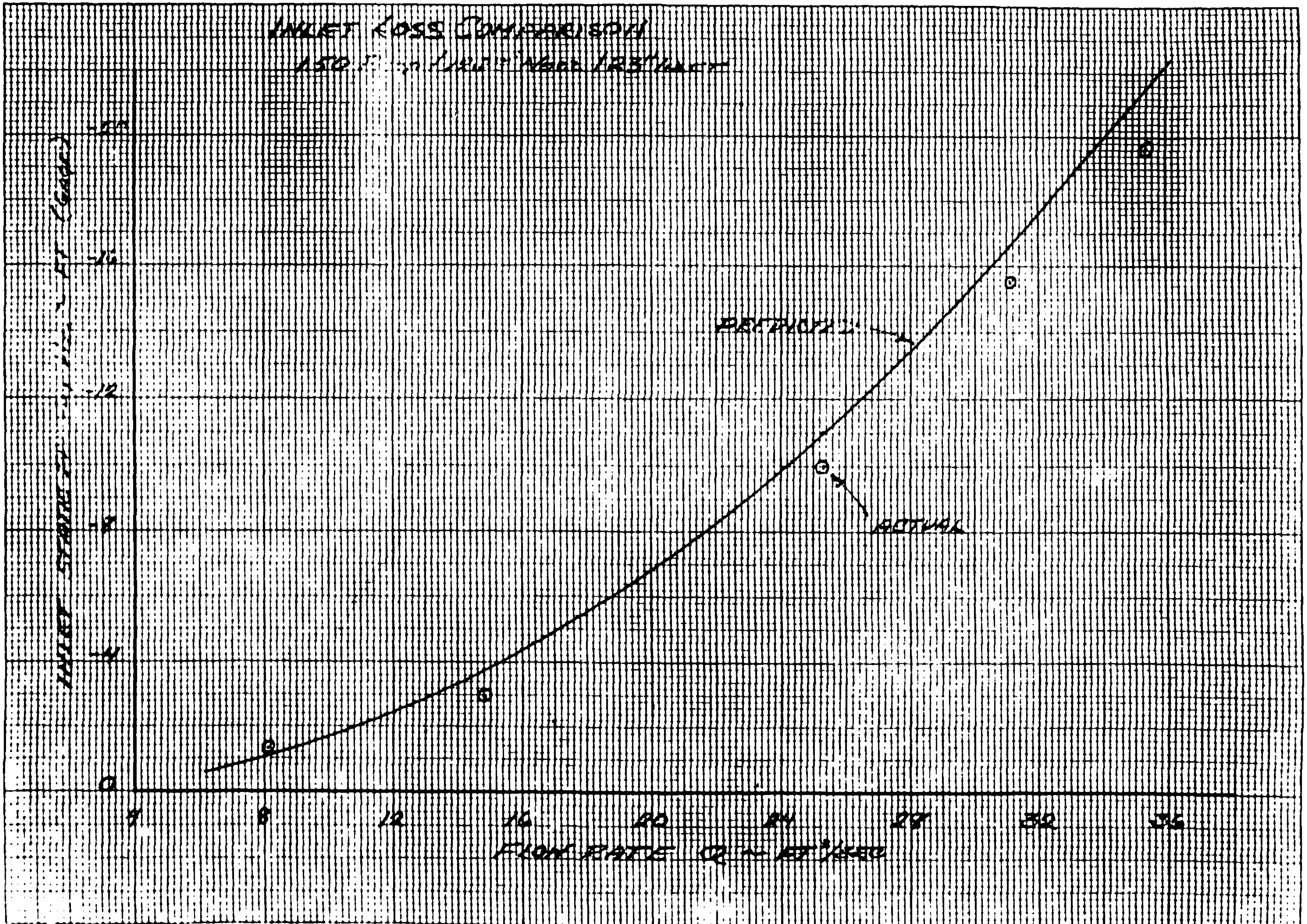
$$\frac{V_I^2}{2g} = \left(\frac{Q}{1.0495}\right)^2 \frac{1}{2(32.2)} = .0143\, Q^2$$

$$H_{I_S} = 0 - .00287\, Q^2 - .0143\, Q^2$$

$$H_{I_S} = -.01719\, Q^2 \qquad \text{(PREDICTED)}$$

$$H_{I_S} = APSI\left(\frac{144}{62.4}\right) = 2.309\, APSI \qquad \text{(ACTUAL)}$$

RUN #	Q	PRED H_{I_S}	APSI	ACTUAL H_{I_S}
212	8.07	-1.12	-.56	-1.29
213	14.76	-3.74	-1.28	-2.95
214	20.04	-6.90	-1.17	-2.70
215	25.30	-11.00	-4.31	-9.95
216	31.10	-16.63	[illegible]	[illegible]
217	35.38	-21.52	[illegible]	[illegible]


INLET LOSS COMPARISON
ACTUAL
0
-4
-8
-12
-16
-20
4
8
12
16
20
24
28
32
36
FLOW RATE Q ~ FT³/SEC

INLET LOSS COMPARISON (BOLLARD TEST)

1.50 PROP. / 12.25 NOZZ. / 19.5" INLET

$$H_{I_s} = H_o - HL_I - \frac{V_I^2}{2g}$$

$$H_o = 0$$

$$HL_I = .003755\,Q^2$$

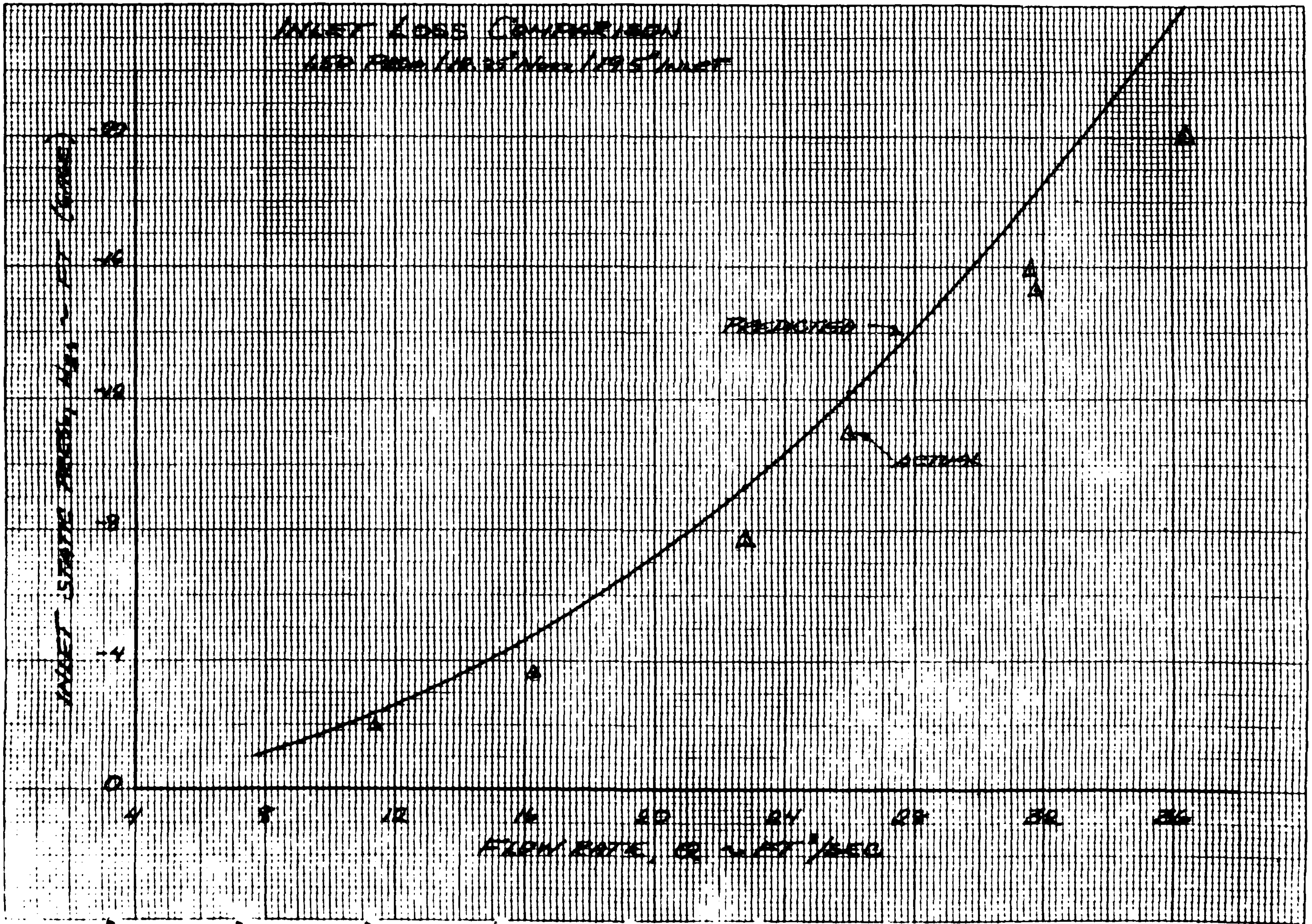
$$\frac{V_I^2}{2g} = \left(\frac{Q}{1.0435}\right)^2 \frac{1}{2(32.2)} = .0143\,Q^2$$

$$H_{I_s} = 0 - .003755\,Q^2 - .0143\,Q^2$$

$$H_{I_s} = -.018055\,Q^2$$ (PREDICTED)

$$H_{I_s} = APSI\left(\frac{144}{62.4}\right) = 2.308\,APSI$$ (ACTUAL)

RUN #	Q	PRED H_{I_s}	APSI	ACTUAL H_{I_s}
228	11.41	-2.35	-.86	-1.98
229	16.25	-4.77	-1.56	-3.60
230	22.06	-7.35	-2.60	-6.02
231	26.04	-12.24	-4.36	-10.33
232	31.77	-18.22	-6.65	-15.35
232	31.65	-18.09	-6.88	-15.88
233	36.35	-23.86	-8.67	-20.01



INLET LOSS COMPARISON
PREDICTED
ACTUAL
0
4
8
12
16
20
4
8
12
16
20
24
28
32
36
FLOW RATE, Q ~ FT³/SEC

INLET LOSS COMPARISON

1.5 PROP / 12.25 NOZZ / 33" INLET

$$H_{IS} = H_0 - HL_I - \frac{V_I^2}{2g}$$

$H_0 = 0$

$HL_I =$ .00[illegible] Q^2

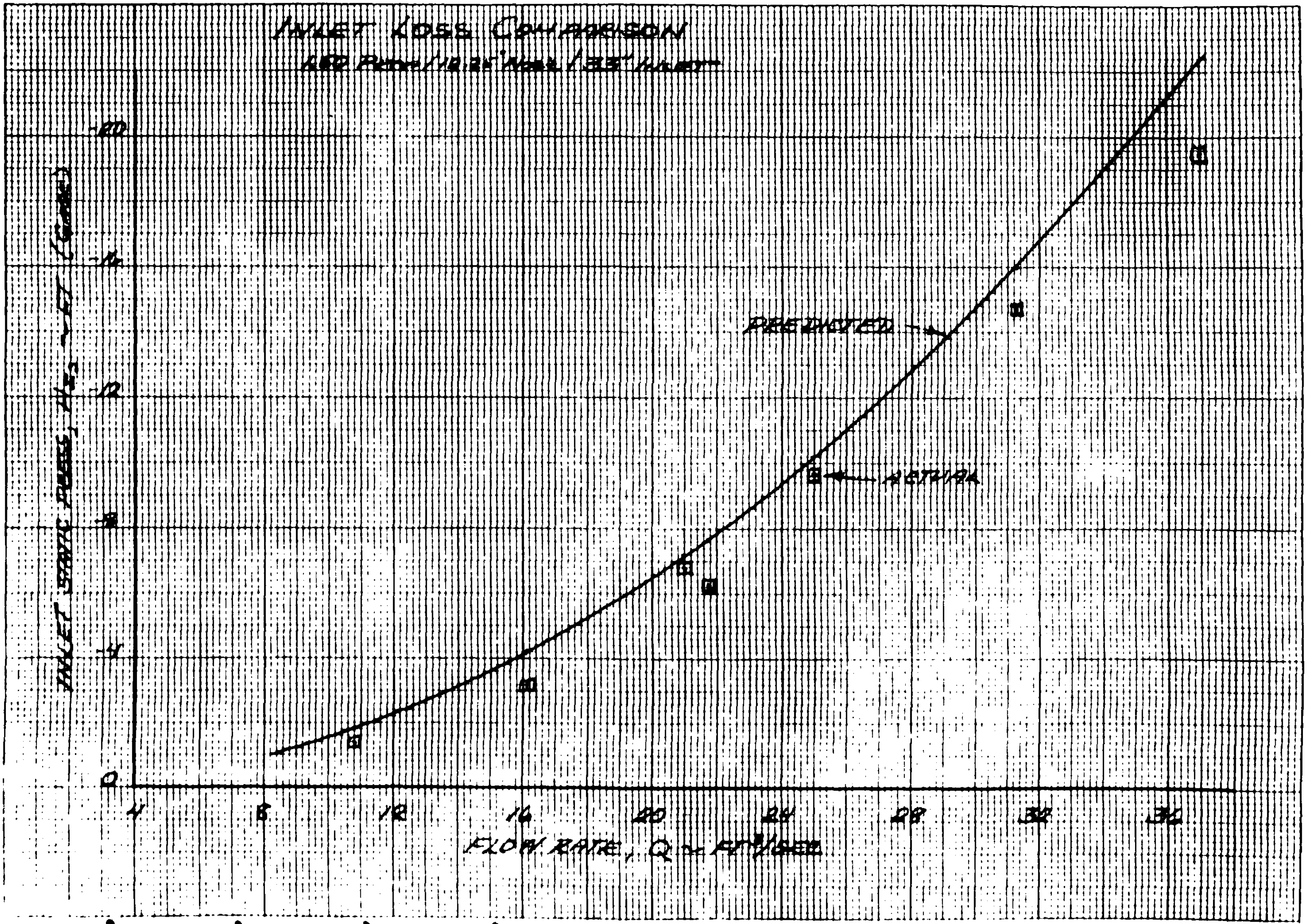
$\frac{V_I^2}{2g} = \left(\frac{Q}{[illegible]}\right)^2 [illegible] = .[illegible] Q^2$

$H_{IS} = 0 -$.[illegible] Q^2 [illegible] $= Q^2$

$H_{IS} = -$ .01337 Q^2 PREDICTED

$H_{IS} = \Delta PSI \left(\frac{144}{62.4}\right) = 2.308\ \Delta PSI$ (ACTUAL)

RUN	Q	PRED H_{IS}	ΔPSI	ACTUAL H_{IS}
251	10.[illegible]	-1.70	.10	-1.3[illegible]
252	15.57	-4.22	-1.38	-3.18
2[illegible]	21.[illegible]	-[illegible]	-2.91	-6.[illegible]
253	21.56	-7.66	-2.70	-6.23
2[illegible]1	24.[illegible]	-[illegible]	-4.1[illegible]	9.67
2[illegible]	31.2[illegible]	-1[illegible]	-6.37	14.70
256	36.99	-[illegible]	-8.4[illegible]	-[illegible]


INLET LOSS COMPARISON
PREDICTED
ACTUAL
-20
-16
-12
-8
-4
0
4
8
12
16
20
24
28
32
36
FLOW RATE, Q ~ FT³/SEC

INLET PRESSURE RECOVERY COMPARISON

1.5M PROP / 12.25 NOZ. / 23" INLET O

$$H_0 = \underset{\substack{\text{SPEED}\\\text{TESTS}}}{H_{I_S}} - \underset{\substack{\text{BOLLARD}\\\text{TESTS}}}{H_{I_S}}$$

$$\underset{\substack{\text{SPEED}\\\text{TEST}}}{H_{I_S}} = \text{[illegible]} \left(\frac{\text{[illegible]}}{\text{[illegible]}}\right) = 2.308\ \text{[illegible]}$$

$$\underset{\substack{\text{BOLLARD}\\\text{TEST}}}{H_{I_S}} = -.01719\,Q^2$$

(FROM INLET LOSS [illegible])

$$H_0 = 2.308\,(\text{PSI}) + .01719\,Q^2$$

([illegible])

RUN #	Q	V_0	PSI	H_0
201	16.[illegible]	[illegible]	+[illegible]	9.4
202	32.95	[illegible]	−2.[illegible]	11.[illegible]
203	[illegible]	[illegible]	−4.29	18.09
204	[illegible]	[illegible]	−3.[illegible]	19.80
205	42.05	[illegible]	−5.[illegible]	17.[illegible]
206	[illegible]	[illegible]	+[illegible]	15.84
207	[illegible]	[illegible]	[illegible]	29.25
208	[illegible]	12.46	[illegible]	[illegible]
209	[illegible]	12.35	[illegible]	[illegible]
210	[illegible]	[illegible]	[illegible]	[illegible]
211	[illegible]	[illegible]33	[illegible]	[illegible]
218	7.25	[illegible]	−.43	[illegible]
219	3[illegible]	32.[illegible]	−4.45	[illegible]
220	4.00	39.62	−6.24	[illegible]

$$H_0 = \frac{V_0^2}{2g} = \frac{V_0^2}{2(32.2)}$$

V_0	H_0
[illegible]	[illegible]
[illegible]	6.20
[illegible]	13.95
[illegible]	24.[illegible]

INLET PRESSURE RECOVERY (COMPARISON)

150 PROP / 12.25" NOZ. 17.5" INLET △

$H_o = H_{I_s\,\text{SPEED TEST}} - H_{I_s\,\text{BOLLARD TEST}}$

$H_{I_s\,\text{SPEED TEST}} = \Delta PSI\ (\text{[illegible]}) = 2.308\ \Delta PSI$

$H_{I_s\,\text{BOLLARD TEST}} \quad -.018055\,Q^2$ (FROM [illegible])

$H_o = 2.308\ \Delta PSI + .018055\,Q^2$ ([illegible])

RUN #	Q	V_o	ΔPSI	ACTUAL H_o
221	10.37	[illegible]	-.36	1.11
222	16.06	[illegible]	-.89	2.60
223	15.54	7.54	-.79	2.08
224	33.21	22.77	-3.7[illegible]	12.71
225	31.9[illegible]	29.44	-4.[illegible]	12.06
226	[illegible]	[illegible]	-2.[illegible]	6.19
227	[illegible]	12.[illegible]	[illegible]	3.85
22[illegible]	[illegible]	6.20	- [illegible]	1.39
23[illegible]	16.[illegible]	7.3	-.[illegible]	3.05
23[illegible]	34.20	27.38	-3.[illegible]	[illegible]
[illegible]	30.3[illegible]	13.32	-[illegible]	5.[illegible]
[illegible]	[illegible]	37.32	-5.[illegible]	11.[illegible]
[illegible]	33.[illegible]	22.[illegible]	-3.[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	-3.[illegible]	[illegible]
[illegible]	[illegible]	3[illegible]	-3[illegible]	[illegible]
[illegible]	23.[illegible]	[illegible]	-[illegible]	[illegible]
243	14.97	[illegible]	-[illegible]	[illegible]

$H_o =$ [illegible]

V_o	[illegible] H_o
10	[illegible]
20	[illegible]
30	13.[illegible]
40	24.[illegible]

INLET PRESSURE RECOVERY COMPARISON

1.50 PROP / 12.25" NOZZ / 33" INLET

$$H_o = \underset{\text{SPEED TESTS}}{H_{I_S}} - \underset{\text{BOLLARD TEST}}{H_{I_o}}$$

H_{I_o} [illegible] = 2.308 [illegible]

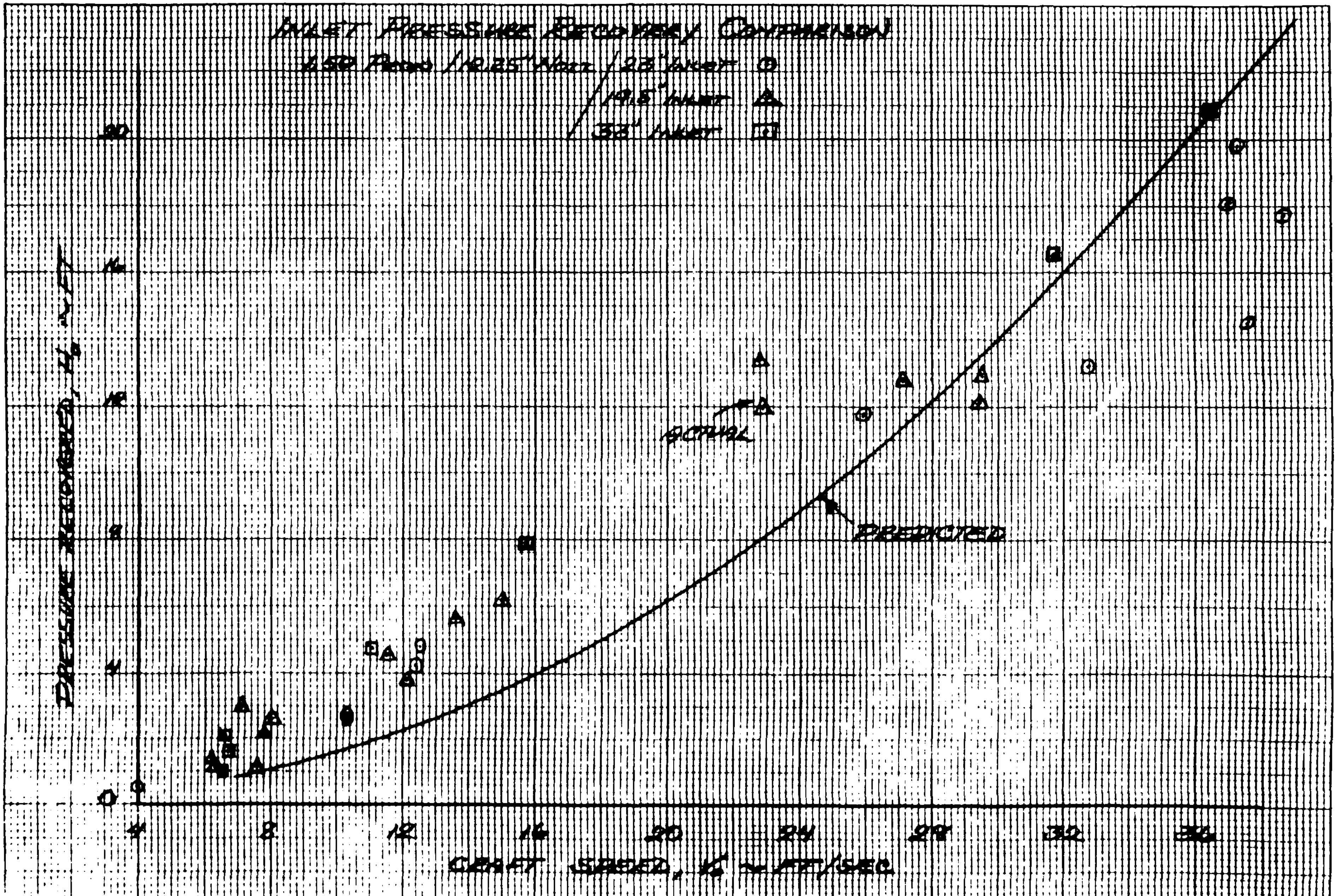
H_{I_S} = $-.016337\,Q^2$ (FROM ALL TESTS [illegible])

$$H_o = 2.308\ \text{FPSI} + .016337\,Q^2$$ (ACTUAL)

RUN #	Q	V_o	H_{I_S}	ACTUAL H_o
544	12.[illegible]	[illegible]	-.61	.95
245	12.35	[illegible]	-1.16	2.07
[illegible]	[illegible]	6.3	[illegible]	.58
[illegible]	33.[illegible]	7	-3.[illegible]	16.49
[illegible]	[illegible]	[illegible]	-3.[illegible]	20.93
[illegible]	69.[illegible]	[illegible]	[illegible]	9.90
[illegible]	[illegible]	[illegible]	-2.[illegible]	4.75

H_o = [illegible] (PREDICTED)

[illegible]	PRE H_o
10	1.55
20	6.20
30	13.95
40	24.80


INLET PRESSURE RECOVERY COMPARISON
12.25" NOZZ
23" INLET
19.5" INLET
32" INLET
ACTUAL
PREDICTED
PRESSURE RECOVERED
CRAFT SPEED
FT/SEC
0
4
8
12
16
20
24
28
32
36

REQUIRED PUMP HEAD COMPARISON

1.50 PROP. / 12.25" NOZZ. / 23" INLET

$H_p = .030761\,Q^2 - .0155\,V_0^2$ (PREDICTED)

RUN	Q	V_0	REQ H_p	ACT H_p
201	16.06	7.28	7.11	4.36
202	32.95	25.87	23.02	20.68
203	40.35	36.74	28.93	26.70
204	40.27	37.28	28.34	27.66
205	42.05	38.56	31.35	29.43
206	27.48	15.08	19.70	16.95
207	29.60	16.07	23.31	18.75
208	26.70	12.48	18.70	11.50
209	26.56	12.35	19.34	11.20
210	21.02	10.29	11.95	6.90
211	20.99	10.33	11.90	6.78
212	8.07	0	2.00	2.48
213	14.76	0	6.70	6.75
214	20.74	0	12.35	12.78
215	25.30	0	19.69	20.94
216	31.10	0	29.75	31.33
217	35.36	0	38.50	39.20
218	9.25	3.95	2.39	2.08
[illegible]	36.74	32.[illegible]	25.30	24.86
220	41.30	37.[illegible]	29.77	28.62

REQUIRED PUMP HEAD COMPARISON

1.50 PROP / 12.25" NOZZ. / 19.5" INLET

$H_P = .031767\, Q^2 - .0155\, V_0^2$ (PREDICTED)

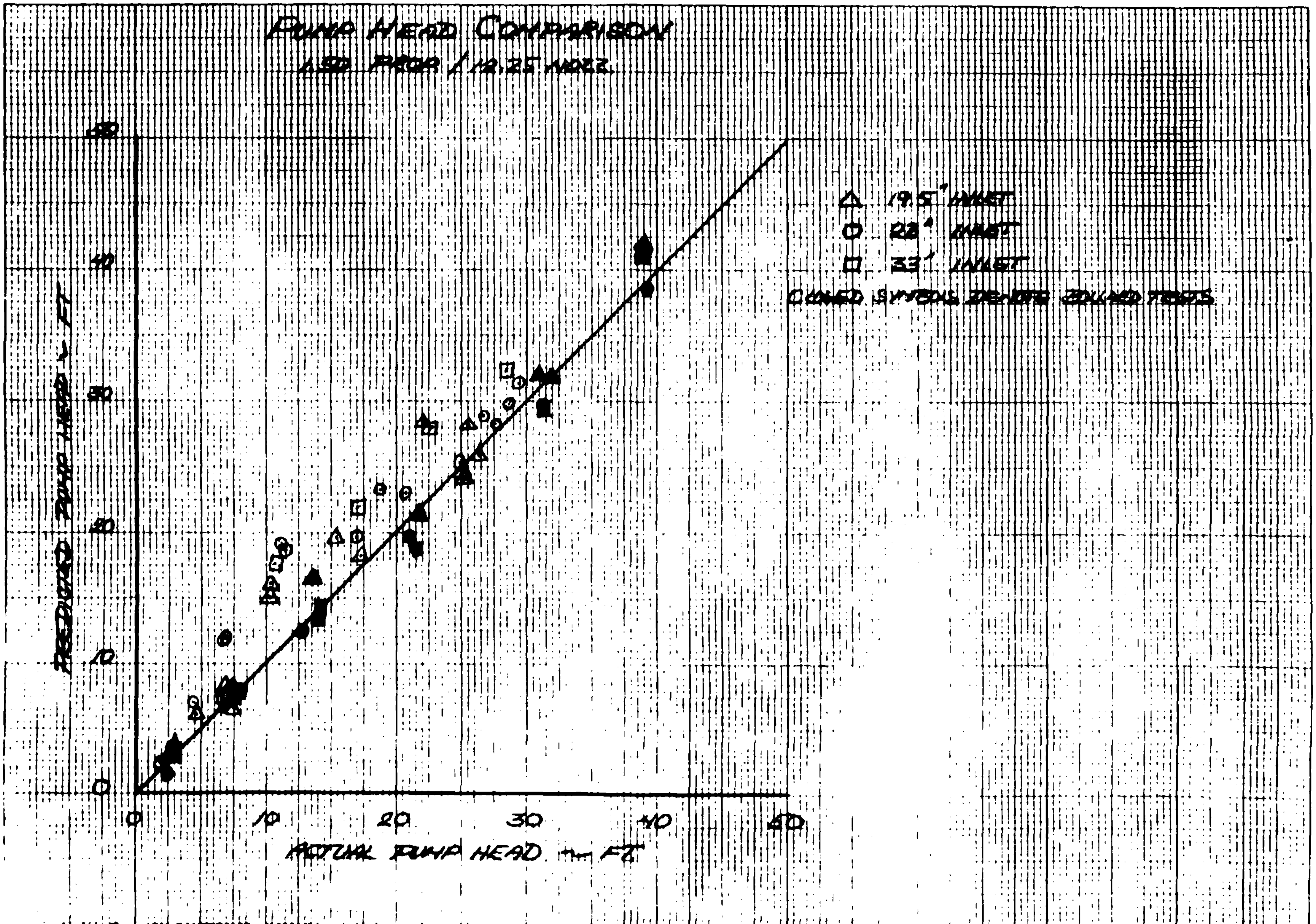
RUN #	Q	V_0	PRED HP	MEAS HP	
221	10.37	6.29	2.60	2.93	
222	16.06	7.97	7.21	7.27	
223	15.14	7.84	6.72	7.33	
224	33.[illegible]	22.70	26.18	25.48	
225	34.36	29.44	24.11	25.21	
226	26.86	15.02	18.28	17.32	
227	23.39	12.10	15.11	9.22	
228	11.41	0	4.14	3.01	
229	16.25	0	8.39	7.40	
230	22.76	0	16.46	13.55	
231	26.[illegible]	0	21.54	21.58	
232	31.77	0	32.06	30.90	
232	31.[illegible]	0	31.82	31.68	
233	36.35	0	41.97	38.69	
234	11.71	.70	3.76	3.04	
235	16.82	7.13	8.20	6.93	
236	34.20	27.08	25.79	26.33	
237	30.36	13.32	26.53	[illegible]	α
238	30.31	37.32	21.69	28.78	>
239	33.74	22.60	28.11	21.45	
240	34.52	29.47	24.61	25.35	
241	26.67	13.30	19.72	15.44	
242	23.94	[illegible]	16.16	10.23	
243	14.79	7.56	6.23	4.59	

Required Pump Head Comparison

1.5D Prop. / 12.25' Noz. / 33' Inlet

$H_p = .030049\,Q^2 - V_o^2$ (Predicted)

Run #	Q	V_o	Pred H_p	Act H_p
244	12.02	5.31	3.90	3.05
245	17.05	6.62	8.06	6.59
246	16.27	6.67	7.26	6.68
247	38.00	31.74	27.71	22.05
248	42.12	36.74	32.39	24.41
249	29.27	15.74	21.90	16.95
250	25.43	11.02	17.55	10.57
251	10.77	0	3.49	3.42
252	16.07	0	7.76	7.84
253	21.00	0	13.25	14.09
253	21.66	0	14.10	14.15
254	24.96	0	18.72	21.60
255	31.28	0	29.40	31.34
256	36.99	0	41.11	39.42


PUMP HEAD COMPARISON
ASD PROP / 12.25 NOZZ.
19.5' INLET
22' INLET
33' INLET
CLOSED SYMBOLS DENOTE
PREDICTED PUMP HEAD ~ FT
ACTUAL PUMP HEAD ~ FT
0
10
20
30
40
50

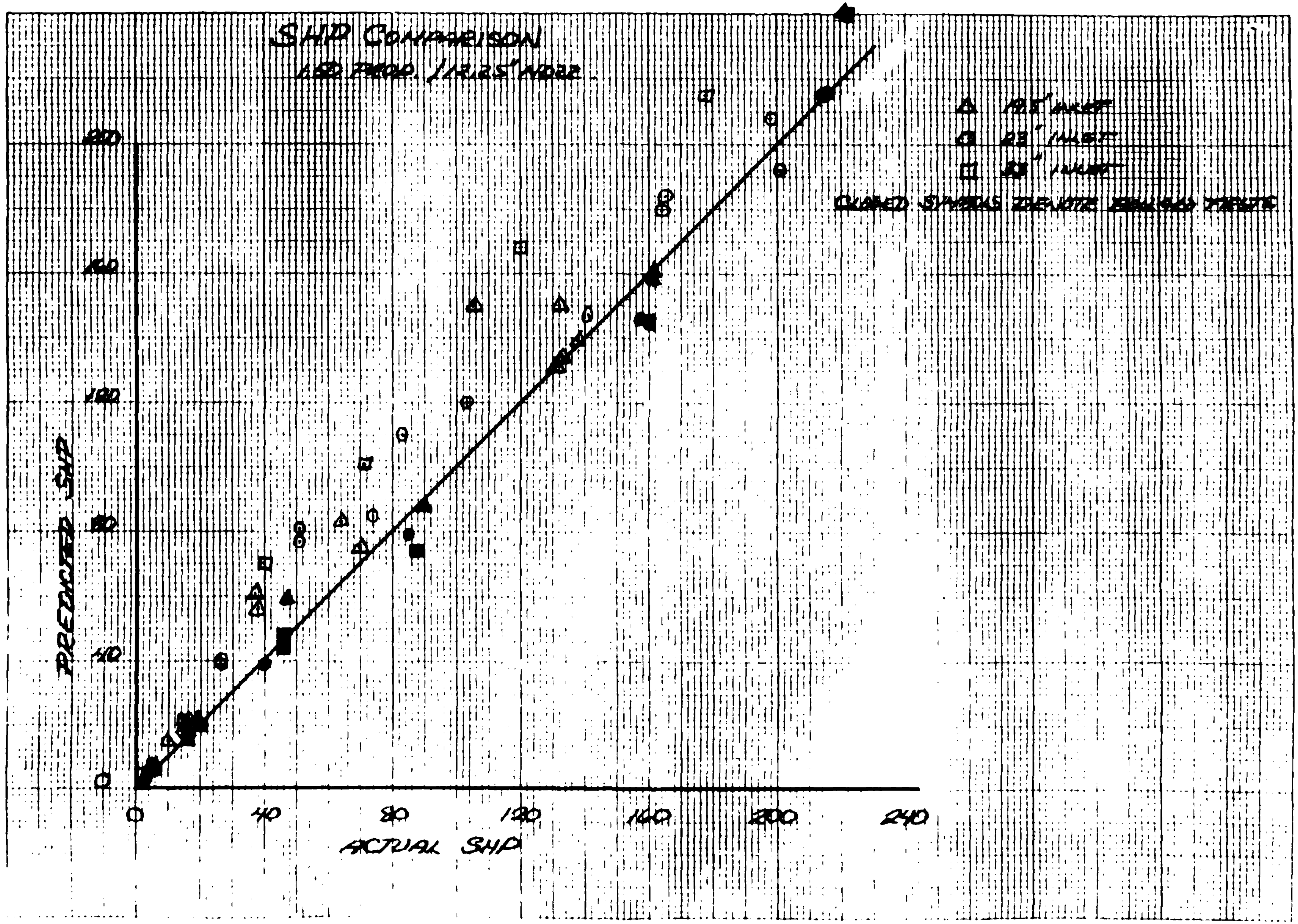
SHP COMPARISON

$SHP = .1577\, Q\, H_p$ (PREDICTED)

RUN #	PROP	NOZZ	INLET	Q	PRED. Hp	PRED SHP	ACTUAL SHP	
201	1.50	12.25	23"	16.06	7.11	18	13	
202				32.95	23.02	120	103	
203				40.35	28.93	184	165	
204				40.27	28.34	180	164	
205				42.05	31.35	208	195	
206				27.48	19.70	85	74	
207				29.60	23.31	110	83	
208				26.20	16.70	77	57	
209				26.56	19.34	91	57	
210				21.02	11.95	40	26	
211				20.99	11.90	39	26	
212				8.07	2.00	3	3	
213				14.76	6.70	16	16	
214				20.04	12.35	39	40	Bollard Tests
215				25.30	19.67	79	85	
216				31.10	29.25	146	157	
217				35.38	36.70	215	215	
218				9.25	2.39	4	2	
219				36.74	25.70	147	141	
220				41.00	29.77	192	201	
221	1.50	12.25	19.5"	10.37	2.80	5	5	
222				16.06	7.21	18	[illegible]	
223				15.54	6.72	16	[illegible]	
224				33.81	28.18	150	[illegible]	
225				34.38	24.11	131	[illegible]	
226				26.18	18.28	75	77	
227				23.39	15.11	56	[illegible]	
228				11.41	4.4	7	[illegible]	
229				16.25	8.79	22	19	
230				22.76	[illegible]	59	[illegible]	
231				26.04	21.54	88	70	Bollard Tests
232				31.77	32.06	161	161	
232				31.65	31.82	159	161	
233				36.35	41.97	241	221	
234				11.71	3.76	7	5	
235				16.82	9.20	22	16	
236				34.20	25.79	139	135	
237				30.36	26.53	127	[illegible]	
238				36.91	21.69	126	192	
239				33.74	28.11	150	135	
240				34.62	24.61	134	133	
241				26.67	19.72	83	64	
242				23.94	16.16	61	37	
243				14.97	6.23	15	10	

SHP Comparison

Run #	Prop	Nozz.	Inlet	Q	Pred. H_o	Pred. SHP	Actual SHP	
244	1.50	12.25	33"	12.02	3.90	7	5	
245				17.05	8.06	22	15	
246				16.27	7.26	19	16	
247				38.06	27.91	168	120	
248				42.12	32.39	215	178	
249				29.27	21.90	101	71	
250				25.43	17.55	70	40	
251				10.77	3.49	6	5	
252				16.07	7.76	20	27	
253				21.00	13.25	44	46	
253				21.66	14.10	48	46	Bollard Tests
254				24.96	18.72	74	86	
255				31.28	29.40	145	160	
256				36.79	41.11	240	222	


SHP COMPARISON
23' INLET
PREDICTED SHP
ACTUAL SHP
0
40
80
120
160
200
240

Cavitation Limits (Baseline Tests)

1.50 Prop/1225 Nozzle

$$S = \frac{21.19\, N \sqrt{Q}}{(H_{Is} - H_V)^{3/4}}$$

$$H_{Is} = H_{ATM} + \Delta PSI\left(\frac{144}{62.4}\right) + .75$$

$$H_{ATM} = 32.12'$$ (100 °F)

$$H_{Is} = 32.12 + 2.308\Delta PSI + .75 = 32.87 + 2.308\Delta PSI$$

$$H_V = 1.00'$$

$$S = \frac{21.19\, N \sqrt{Q}}{(32.87 + 2.308\Delta PSI - 1.00)^{3/4}} = \frac{21.19\, N \sqrt{Q}}{(31.87 + 2.308\Delta PSI)^{3/4}}$$

Run #	Inlet	N	Q	ΔPSI	S	T_Q	K_T
212	23"	633	807	-.1[illegible]	6930	168	.42
213	⊙	919	14.70	-1.28	6000	4.8	.54
214		1213	2774	-1.17	[illegible]	867	.59
215		[illegible]	[illegible]	4.31	19889	1420	.62
216		[illegible]	[illegible]	6.72	[illegible]	2.25	.3
217		[illegible]	[illegible]	8.49	[illegible]	[illegible]	.3
[illegible]	19.5	[illegible]	[illegible]	.36	3328	204	.52
[illegible]	△	[illegible]	[illegible]	[illegible]	6340	[illegible]	[illegible]
[illegible]		1211	[illegible]	[illegible]	10690	[illegible]	.3
231		1500	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
232		1819	[illegible]	6.05	[illegible]	[illegible]	.3
[illegible]		1819	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
233		2042	36.75	[illegible]	40621	[illegible]	.3
[illegible]	33	587	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	⊡	920	[illegible]	[illegible]	[illegible]	[illegible]	.3
[illegible]		1215	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]	[illegible]	25592	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]	[illegible]	33231	[illegible]	.3

CAVITATION LIMITS (CAPED TESTS)

1.50 PROP/1.225 NOZZ.

$$S = \frac{21.19\,N\,\sqrt{Q}}{(H_{s} - H_{v})^{3/4}}$$

$$H_{s} = H_{ATM} + \Delta PSI\left(\frac{144}{62.4}\right) + .[illegible]$$

$$H_{ATM} = 32.12' \qquad (1{,}500\ [illegible])$$

$$H_{s} = 32.[illegible] + 2.[illegible]\,\Delta PSI + .[illegible] = 32.[illegible] + 2.308\,\Delta PSI$$

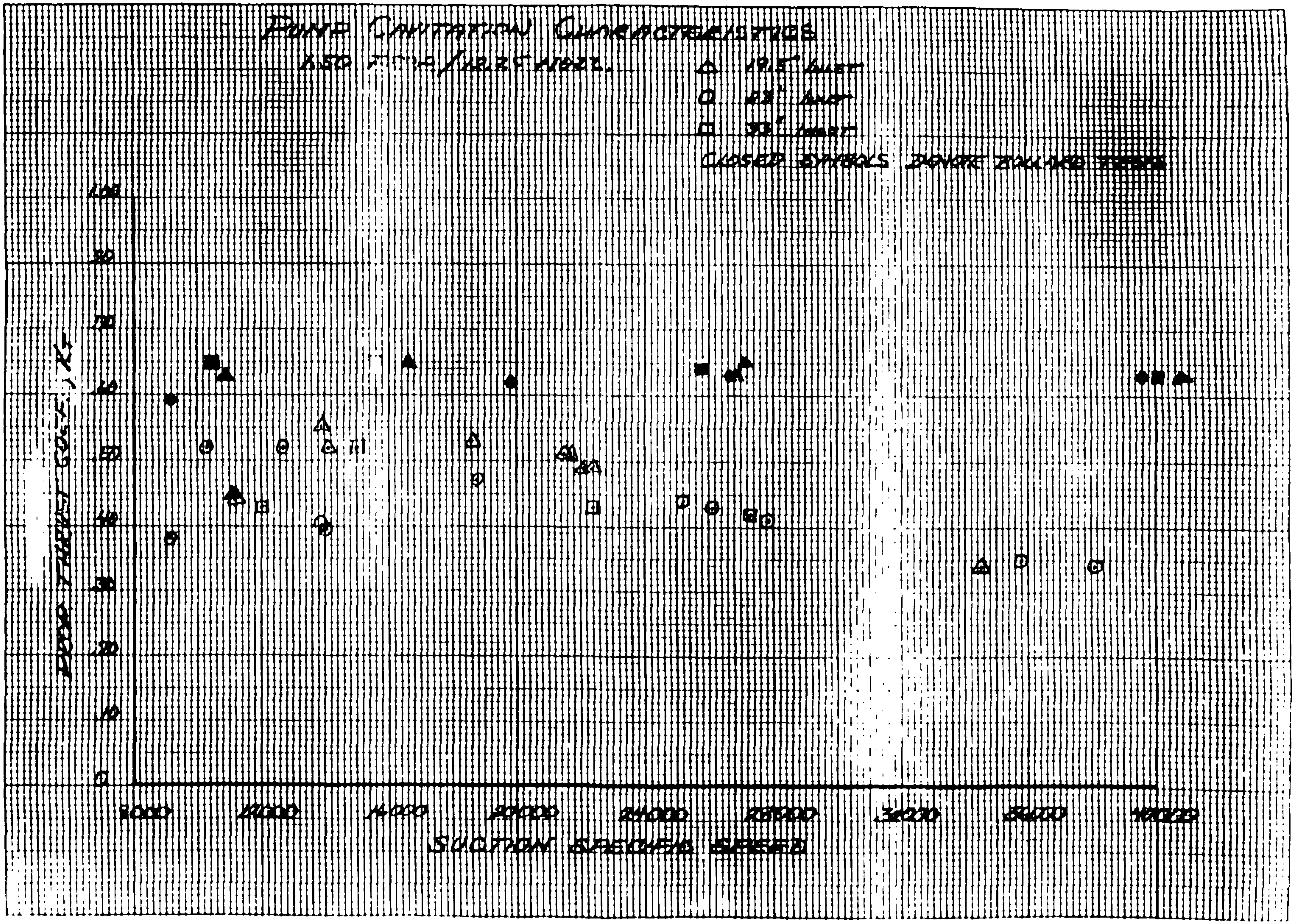
$$S = \frac{21.19\,N\,\sqrt{Q}}{(32.[illegible] + 2.308\,\Delta PSI - 1)^{3/4}} = \frac{21.19\,N\,\sqrt{Q}}{(31.8[illegible] + 2.308\,\Delta PSI)^{3/4}}$$

RUN #	[illegible]	N	Q	ΔPSI	S	T_s	K
[illegible]	23	[illegible]	16.06	+2.[illegible]	[illegible]	296	.41
[illegible]	[illegible]	1[illegible]23	32.95	-2.99	[illegible]	1403	.4[illegible]
[illegible]		21[illegible]	40.35	-4.29	[illegible]	1811	.41
[illegible]		209[illegible]	40.[illegible]	-3.[illegible]	[illegible]	1876	.43
[illegible]		[illegible]	42.[illegible]	-5.[illegible]	[illegible]	[illegible]	.35
20[illegible]		14[illegible]	[illegible]	+1.24	[illegible]	[illegible]	.52
[illegible]		[illegible]	[illegible]	-[illegible]	[illegible]	12[illegible]	[illegible]
[illegible]		13[illegible]	[illegible]	-5.[illegible]	[illegible]	[illegible]	.40
209		13[illegible]	[illegible]	-3.[illegible]	14070	[illegible]	.39
210		[illegible]	[illegible]	-[illegible]	[illegible]	[illegible]	.35
211		[illegible]	[illegible]	-2.[illegible]	9091	[illegible]	.36
218		[illegible]	9.25	-[illegible]	[illegible]	[illegible]	.58
219		19[illegible]	36.[illegible]	-4.[illegible]	25[illegible]	[illegible]	.44
220		[illegible]	41.00	-6.64	[illegible]	[illegible]	.34

Cavitation Limits (Speed Tests)

1.50 Prop/12.25" Nozz (Cont.)

Run #	Inlet	N	Q	ΔPSI	S	T_s	K
221	19.5	610	[illegible]37	-.36	3165	179	.54
222	△	872	16.06	-.89	5937	493	.52
223		883	15.54	-.99	5815	497	.54
224		1549	33.[illegible]	-3.04	21525	1728	.51
225		1873	34.38	-4.02	22457	1710	.49
226		1458	20.8	2.68	13855	1175	.55
227		12[illegible]	2339	2.01	11238	593	.44
234		543	[illegible]	.48	3570	206	.50
235		862	[illegible]82	.89	5871	470	.63
236		1875	34.20	3.10	21727	1786	.51
237		520	30.36	.54	4664	133	.49
238		2412	36.91	5.10	34510	766	.34
239		1678	33.[illegible]	3.[illegible]	18620	1489	.53
240		1872	34.62	3.28	221[illegible]8	1699	.49
241		14[illegible]	[illegible]	3.[illegible]	14078	1347	.52
242		[illegible]	23.71	2.5[illegible]	11186	594	.45
243		795	[illegible]77	1.25	5221	311	.49
244	33"	530	12.[illegible]	[illegible]	3000	207	.57
245	⌶	830	17.35	[illegible]	5202	447	.61
246		8[illegible]	16.27	[illegible]	5245	453	.60
247		1[illegible]	36.[illegible]	3	223[illegible]3	1536	.48
248		2146	42.12	3.[illegible]	[illegible]	[illegible]	.42
249		1495	29.[illegible]	2.64	1[illegible]	1150	.52
250		1296	[illegible]3	-2.52	[illegible]2009	[illegible]6	[illegible]


PUMP CAVITATION CHARACTERISTICS
19.5° INLET
23° INLET
30° INLET
CLOSED SYMBOLS
SUCTION SPECIFIC SPEED

Cavitation Limits (Bollard Tests)

1.50 Prop.

$$\sigma_T = \frac{H_{I_3} - H_{VAP}}{\frac{V_T^2}{2g}}$$

$$H_{I_3} = H_{ATM} + APSI\left(\frac{144}{62.4}\right) + .75$$

$$H_{ATM} = 32.12'$$

$$H_{I_3} = 32.12 + 2.308\,APSI + .75 = 32.87 + 2.308\,APSI$$

$$H_{VAP} = 1.00'$$

$$\frac{V_T^2}{2g} = \left(\frac{Q}{A}\right)^2\frac{1}{2g} + \left(\frac{\pi D N}{60}\right)^2\frac{1}{2g} = \frac{Q^2}{(1.0434)^2(2)(32.2)} + \left(\frac{1.167\pi N}{60}\right)^2\frac{1}{2g}$$

$$= .0143\,Q^2 + .000058\,N^2$$

$$\sigma_T = \frac{32.87 + 2.308\,APSI - 1}{.0143\,Q^2 + .000058\,N^2} = \frac{31.87 + 2.308\,APSI}{.0143\,Q^2 + .000058\,N^2}$$

$$K_T = \frac{T_3}{\rho n^2 D^4} = \frac{T_3}{(1.94)\left(\frac{N}{60}\right)^2\left(\frac{14}{12}\right)^4} = 1002\,\frac{T_3}{N^2}$$

Run*	Nozz	Wkt	Q	APSI	N	σ_T	T_3	K_T
212	12.2'	23'	8.07	-.52	633	.27	166	.42
213		⊙	[illegible]	-1.26	719	.56	458	.54
214			20.34	-1.17	1213	.32	[illegible]	.59
215			25.30	4.31	1518	.15	[illegible]	.62
216			[illegible]	6.72	1840	.08	[illegible]	.63
217			35.36	8.49	2057	.05	[illegible]	.63
226	12.25	17.5	11.41	[illegible]	630	.20	[illegible]	.52
229		△	[illegible]	[illegible]	910	.55	[illegible]	.61
230			[illegible]	[illegible]	1211	.27	[illegible]	.63
231			[illegible]	[illegible]	1500	.15	[illegible]	[illegible]
232			[illegible]	[illegible]	1819	.08	[illegible]	[illegible]
232			[illegible]	6.06	1519	.08	[illegible]	[illegible]
233			30.35	[illegible]	2042	.05	[illegible]	.63
251	12.25	33	[illegible]	[illegible]	587	.41	[illegible]	.67
252		II	[illegible]	1.86	720	.54	[illegible]	.63
253			[illegible]	[illegible]	1215	.27	[illegible]	[illegible]
253			[illegible]	[illegible]	1215	.28	[illegible]	[illegible]
254			[illegible]	[illegible]	1507	.16	[illegible]	[illegible]
255			[illegible]	[illegible]	1827	.08	[illegible]	[illegible]
256			36.79	[illegible]	2055	.05	[illegible]	.63

CAVITATION LIMITS (SPEED TESTS)

150 DROP

$$\sigma_T = \frac{H_{IS} - H_{VAP}}{\frac{V_T^2}{2g}}$$

$$H_{IS} = H_{ATM} + APSI\left(\tfrac{144}{62.4}\right) - .25$$

$$H_{ATM} = 32.12'$$

$$H_{IS} = 32.12 + 2.308\,APSI + .25 = 32.37 + 2.308\,APSI$$

$$H_{VAP} = 1.00'$$

$$\frac{V_T^2}{2g} = \left(\frac{Q}{A}\right)^2 \frac{1}{2g} + \left(\frac{.7\pi D N}{60}\right)^2 \frac{1}{2g} = \frac{Q^2}{(.0434)^2(?)(32.2)} + \left(\frac{1.167\pi N}{60}\right)^2 \frac{1}{2(32.2)}$$

$$= .0143\,Q^2 + .000058\,N^2$$

$$\sigma_T = \frac{32.37 + 2.308\,APSI - 1}{.0143\,Q^2 + .000058\,N^2} = \frac{31.37 + 2.308\,APSI}{.0143\,Q^2 + .000058\,N^2}$$

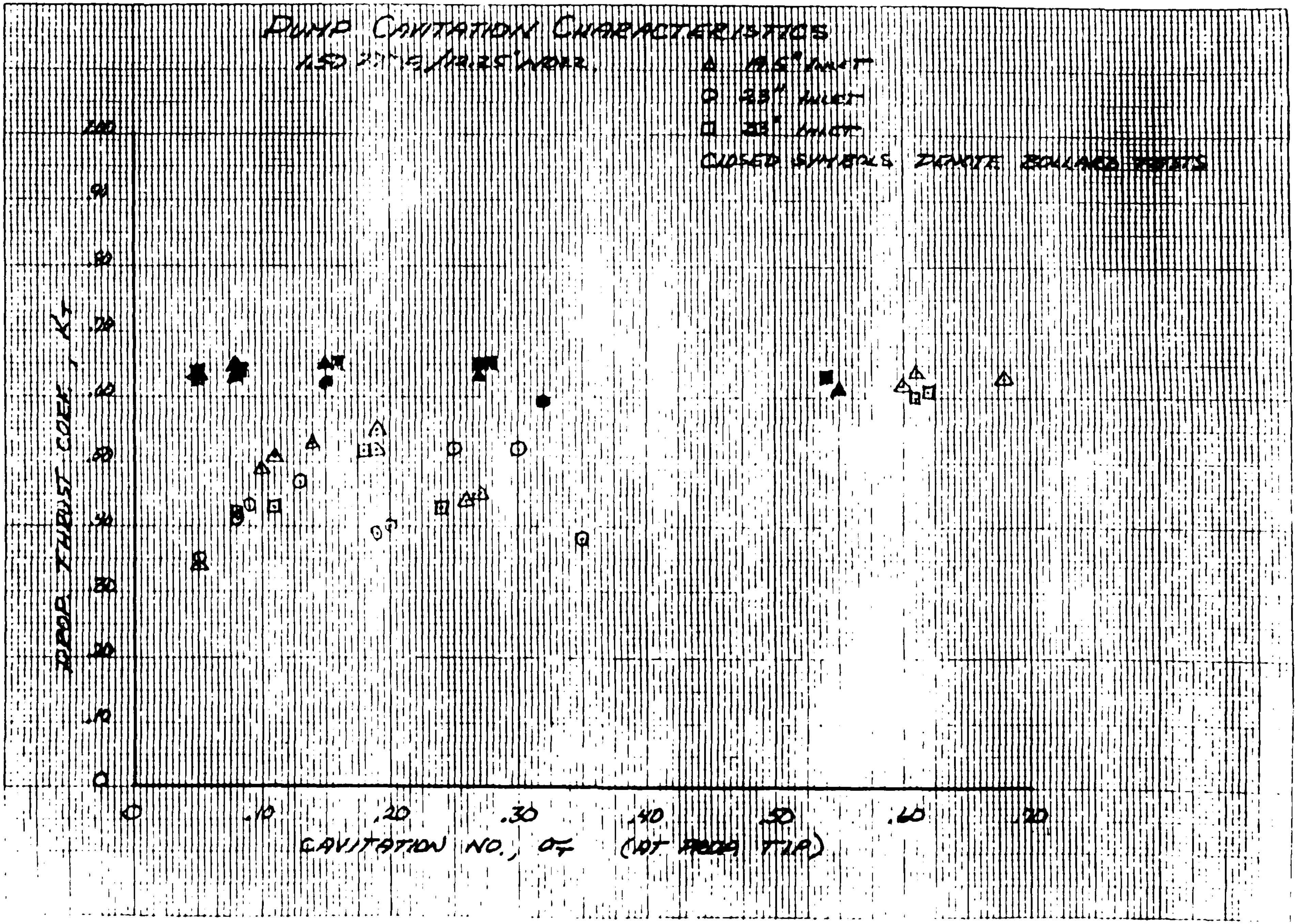
$$K_T = \frac{T_s}{\rho n^2 D^4} = \frac{T_s}{(1.94)\left(\frac{N}{60}\right)^2\left(\frac{?}{?}\right)^4} = 1002\,\frac{T_s}{N^2}$$

RUN #	N_{OZZ}	INLET	Q	APSI	N	σ_T	T_s	K_T
201	12.25	23	16.06	-2.04	848	.51	[illegible]	.41
202		0	32.35	-2.79	1723	.13	[illegible]	.47
203			47.35	-4.29	2101	.08	[illegible]	.41
204			40.27	-3.10	2072	.09	[illegible]	.43
205			[illegible]	-5.52	[illegible]	.05	[illegible]	[illegible]
206			27.45	-1.24	[illegible]	.25	[illegible]	[illegible]
207			29.60	-2.06	[illegible]	.30	[illegible]	[illegible]
208			26.20	-3.30	1374	.20	[illegible]	[illegible]
209			[illegible]	-3.44	1374	.19	[illegible]	.39
210			21.02	[illegible]	1109	.35	[illegible]	.35
211			[illegible]	[illegible]	[illegible]	.35	[illegible]	.35
215			[illegible]	[illegible]	495	2.00	[illegible]	[illegible]
219			[illegible]	[illegible]	1961	.09	[illegible]	[illegible]
220			[illegible]	[illegible]	2400	.05	[illegible]	.34

Cavitation Limits (Speed Tests)

1.50 Prop. (cont.)

Run #	Nozz	Inlet	Q	ACI	N	T_T	T_s	K_T
221	12.25	19.5"	10.37	-.36	610	.34	179	.54
222		△	16.06	-.89	892	.60	493	.62
223			15.54	-.99	883	.61	437	.64
224			33.81	-3.34	1849	.11	1725	.51
225			34.38	-4.22	1873	.10	1710	.49
226			26.18	-2.66	1456	.19	1125	.55
227			23.39	-2.61	1257	.26	693	.44
234			11.71	-.48	643	1.19	206	.50
235			16.82	-.59	562	.68	420	.63
236			34.20	-3.60	1875	.11	1786	.51
237			30.36	-.54	520	1.06	133	.49
238			36.91	-5.10	2412	.05	966	.34
239			33.14	-3.09	1678	.14	1489	.53
240			34.62	-3.75	1872	.10	[illegible]	.49
241			26.67	-3.10	1426	.19	1047	.52
242			23.94	-2.51	1245	.27	[illegible]	.45
243			14.99	-1.25	995	.73	311	.49
244	12.25	33"	12.02	-.61	637	1.19	[illegible]	.51
245		⊡	17.05	-1.16	360	.62	[illegible]	.61
246			16.27	-1.19	872	.61	[illegible]	.60
247			38.26	-3.11	1894	.11	[illegible]	.43
248			42.12	-3.43	[illegible]	.08	1727	.42
249			29.27	-2.[illegible]	[illegible]	.18	[illegible]	[illegible]
250			25.43	-2.52	1296	.24	[illegible]	.43


PUMP CAVITATION CHARACTERISTICS
CLOSED SYMBOLS DENOTE BOLLARD TESTS
PROP THRUST COEF., K_T
CAVITATION NO., σ_T (AT PROP TIP)
0
.10
.20
.30
.40
.50
.60
.70

Cavitation Limit (Bowen Tests)

Prop. Comparison

$$\sigma = \frac{H_{I_s} - H_{VAP}}{V_I^2/2g}$$

$$H_{I_s} = H_{ATM} + \Delta PSI\left(\frac{IN}{[illegible]}\right) + .75$$

$$H_{ATM} = 32.12'$$

$$H_{I_s} = 32.12 + 2.308\,\Delta PSI + .75 = 32.87 + 2.308\,\Delta PSI$$

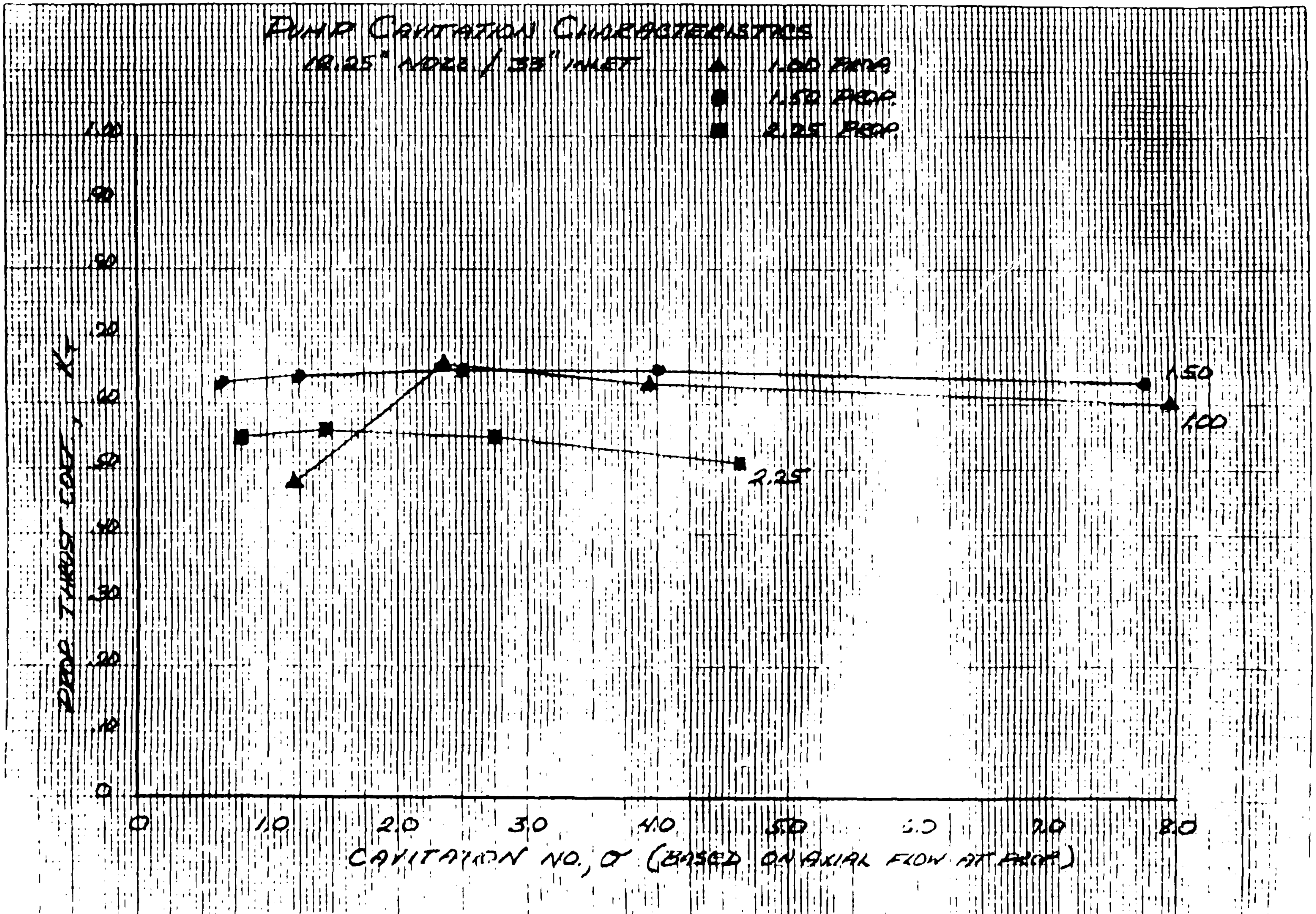
$$H_{VAP} = 1.00'$$

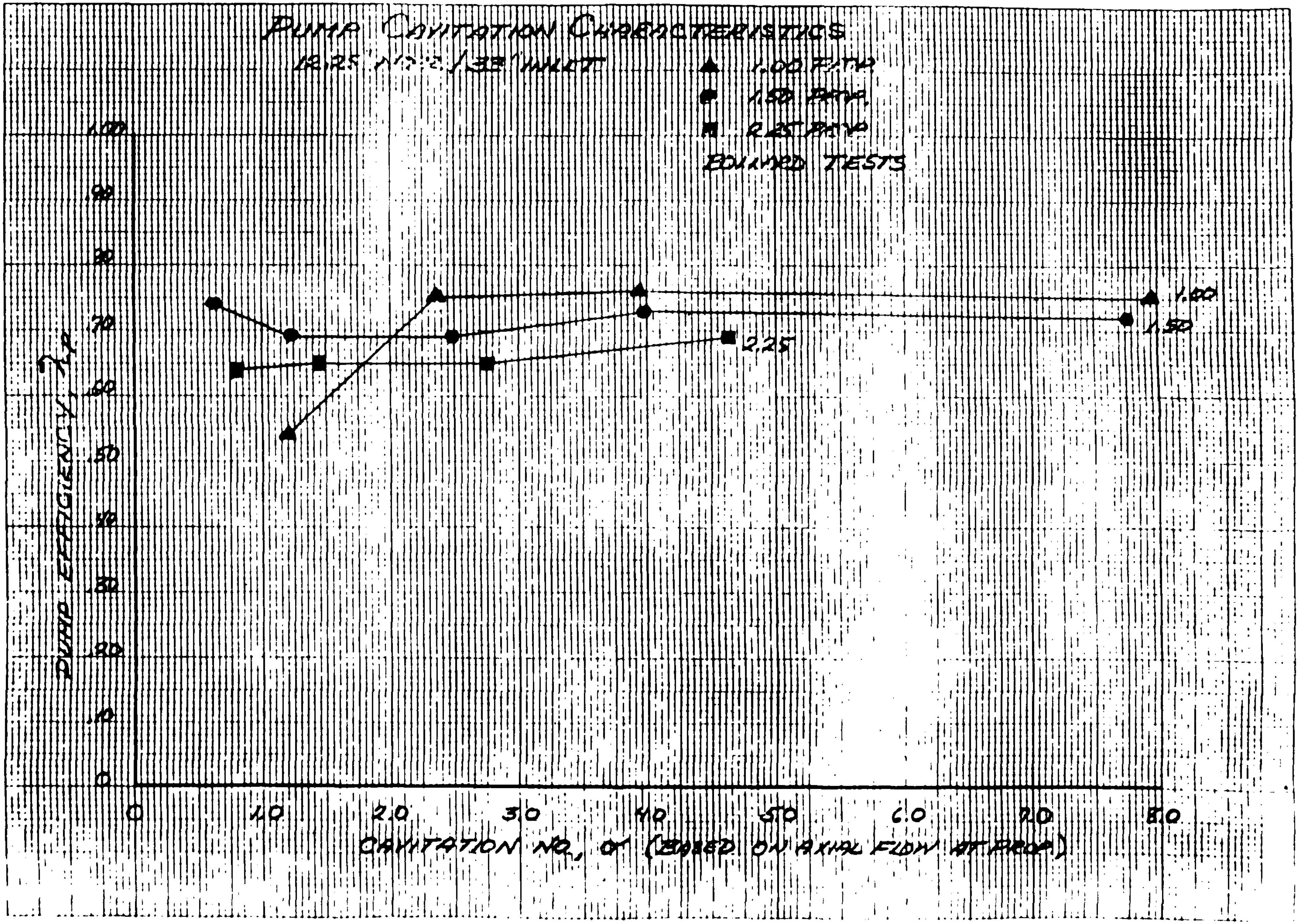
$$\frac{V_I^2}{2g} = \left(\frac{Q}{A}\right)^2 \frac{1}{2g} = \frac{Q^2}{(1.0434)^2 (2)(32.2)} = .0143\,Q^2$$

$$\sigma = \frac{32.87 + 2.308\,\Delta PSI - 1}{.0143\,Q^2} = \frac{31.87 + 2.308\,\Delta PSI}{.0143\,Q^2}$$

$$K_T = \frac{T_s}{\rho n^2 D^4} = \frac{T_s}{1.94 \left(\frac{N}{60}\right)^2 \left(\frac{14}{12}\right)^4} = 1002\,\frac{T_s}{N^2}$$

Run #	Prop	Ht.	Inlet	Q	ΔPSI	T	T_s	N	K_T	σ_p	J
251	1.50	12.25"	33'	10.77	-.20	15.38	232	587	[illegible]	[illegible]	[illegible]
252	○			16.27	-1.38	7.77	[illegible]	720	[illegible]	[illegible]	[illegible]
253				21.00	-2.74	3.78	75[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
254				24.96	-4.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
255				31.28	-6.37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
256				36.79	-5.[illegible]	[illegible]	[illegible]	2055	[illegible]	[illegible]	[illegible]
310	2.25	12.25"	33"	10.[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]	[illegible]	[illegible]
311	□			13.60	-.89	[illegible]	315	[illegible]	[illegible]	[illegible]	[illegible]
312				20.24	-2.03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
313				24.31	-3.69	2.76	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
314				[illegible]	-5.89	1.46	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
315				34.20	-8.08	.79	[illegible]	[illegible]	.55	[illegible]	[illegible]
	1.00	12.25	33"	10.31	-.65	19.98	220	[illegible]	.57	[illegible]	.76
	△			15.71	-1.63	7.96	500	[illegible]	[illegible]	[illegible]	[illegible]
				20.98	-3.05	3.74	700	1200	[illegible]	[illegible]	[illegible]
				25.25	-4.50	2.36	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
				30.61	-6.70	1.19	1670	[illegible]	.48	.54	[illegible]

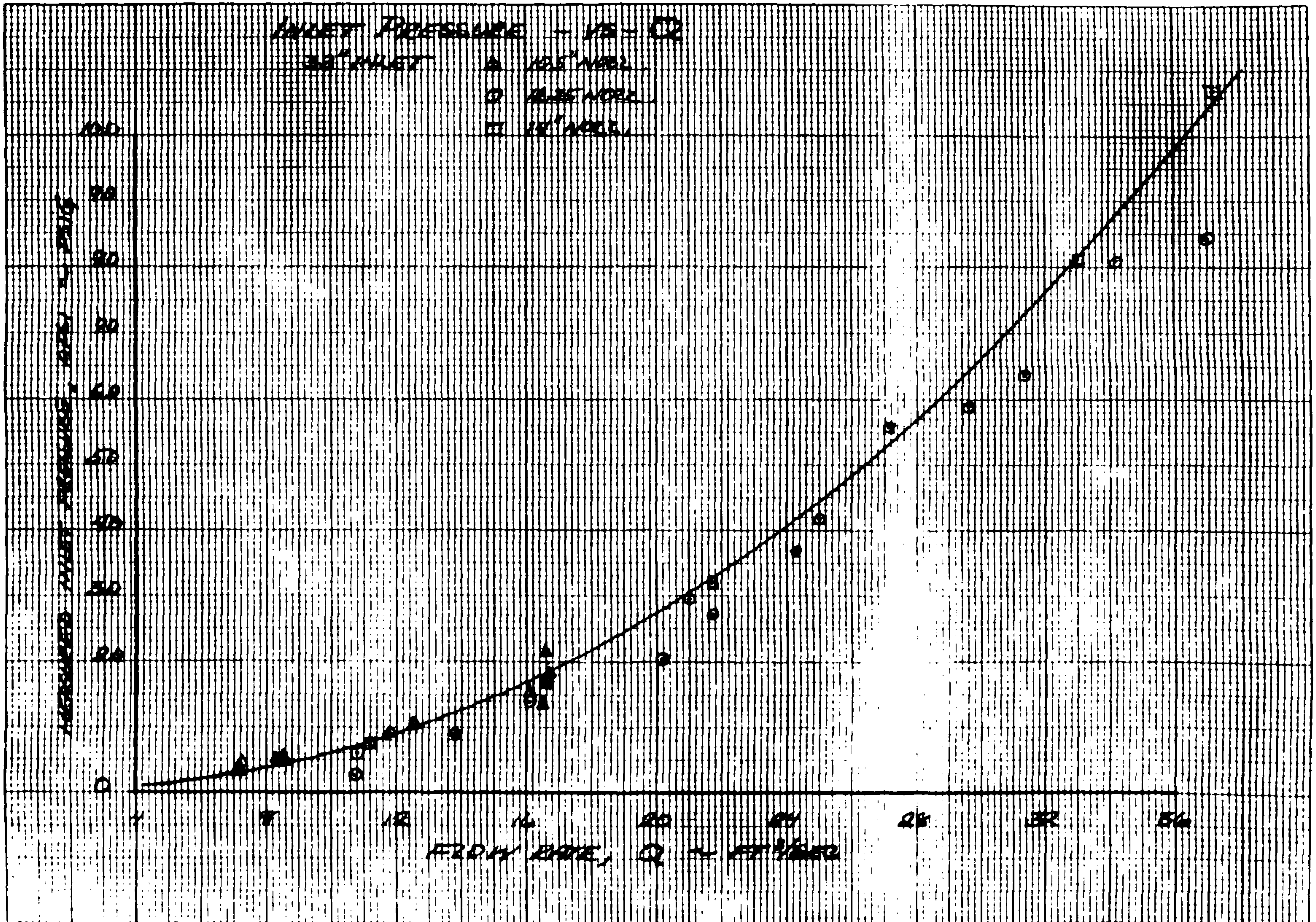

PUMP CAVITATION CHARACTERISTICS
12.25" NOZZ / 33" INLET
1.00 PROP
1.50 PROP
2.25 PROP
1.50
1.00
2.25
PROP THRUST COEF., K_T
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
0
1.0
2.0
3.0
4.0
5.0
7.0
8.0
CAVITATION NO., σ (BASED ON AXIAL FLOW AT PROP)


PUMP CAVITATION CHARACTERISTICS
EDWARD TESTS
1.00
1.50
2.25
PUMP EFFICIENCY
CAVITATION NO., (BASED ON AXIAL FLOW AT PROP)
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00

INLET PRESSURE

33" INLET (BOLLAR. TESTS)

	Run #	Nozz	Q	[illegible]
1.5AR	251	12.2	[illegible]	.30
	252	○	16.33	1.36
	253		21.30	2.34
	253		21.30	2.30
	254		24.96	4.9
	255		31.28	6.32
	256		36.79	8.72
2.25AR	293	10.5'	[illegible].7	.46
	294	△	8.25	.55
	295		12.51	1.02
	296		16.13	1.54
	297		16.54	[illegible]
2.25AR	310	11.[illegible]	10.65	.26
	311	○	13.10	.69
	312		20.24	2.23
	313		24.31	3.[illegible]
	31[illegible]		29.[illegible]	5.69
	31[illegible]		34.10	6.76
2.25AR	33[illegible]	14.[illegible]	11.23	.24
	3[illegible]	□	16.[illegible]	1.00
	[illegible]		21.[illegible]	3.24
	[illegible]		27.10	[illegible]
	[illegible]		32.95	8.[illegible]
	[illegible]		[illegible]	10.[illegible]
1.00AR	[illegible]	10.5"	9.06	.31
	[illegible]	△	8.4[illegible]	[illegible]
	[illegible]		11.25	[illegible]
	[illegible]		16.54	[illegible]
	3[illegible]		16.[illegible]	1.62


INLET PRESSURE - VS - Q
3.5" INLET
FLOW RATE, Q ~ FT³/SEC
4
8
12
16
20
24
28
32
36
0
10
20
30
40
50
60
70
80
90
100

CAVITATION LIMITS (BOLLARD TESTS)

1.50 PROP

$$\sigma = \frac{H_{s_o} - H_{VAP}}{\frac{V_I^2}{2g}}$$

$$H_{I_s} = H_{ATM} + APSI\left(\frac{144}{62.4}\right) + .75$$

$$H_{ATM} = 32.12'$$

$$H_{I_s} = 32.12 + 2.308\,APSI + .75 = 32.87 + 2.308\,APSI$$

$$H_{VAP} = 1.00'$$

$$\frac{V_I^2}{2g} = \left(\frac{Q}{A}\right)^2 \frac{1}{2g} = \frac{Q^2}{(1.0434)^2(2)(32.2)} = .0143\,Q^2$$

$$\sigma = \frac{32.87 + 2.308\,APSI - 1}{.0143\,Q^2} = \frac{31.87 + 2.308\,APSI}{.0143\,Q^2}$$

$$K_T = \frac{T_s}{\rho n^2 D^4} = \frac{T_s}{(1.94)\left(\frac{N}{60}\right)^2\left(\frac{H}{12}\right)^4} = 1002\,\frac{T_s}{N^2}$$

RUN #	NOZ	INLET	Q	APSI	σ	T_s	N	K_T	J	η_p
212	12.25	23	8.07	-.56	32.83	106	623	.42	.60	.73
213	"		14.36	-1.28	9.28	458	[illegible]	.54	.35	.72
214			20.04	-1.17	5.75	367	2.3	.59	.77	.73
215			25.30	-4.31	8.40	[illegible]	[illegible]	.62	.78	.71
2[illegible]			31.10	-6.72	1.15	[illegible]	840	.63	[illegible]	.71
2[illegible]			35.38	-8.49	[illegible]	[illegible]	[illegible]	.63	[illegible]	.73
[illegible]	12.25	[illegible]	11.41	-.86	16.05	[illegible]	630	.52	[illegible]	.62
[illegible]	"		16.25	-1.56	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.70
230			22.36	[illegible]	3.4	[illegible]	[illegible]	.3	[illegible]	.75
231			26.0[illegible]	-4.36	2.15	[illegible]	[illegible]	.5	.61	.71
232			31.07	[illegible]	[illegible]	[illegible]	[illegible]	.3	[illegible]	.69
232			31.65	-6.86	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.70
233			36.35	[illegible]	.63	[illegible]	[illegible]	.3	.33	.73
251	12.25	33'	10.77	[illegible]	8.36	232	587	[illegible]	[illegible]	.61
252	"		16.77	1.36	7.77	[illegible]	720	.63	[illegible]	.72
253			2[illegible]	2.74	3.78	[illegible]	[illegible]	.65	[illegible]	.73
253			2[illegible]	2.77	3.82	760	1215	.65	[illegible]	.75
254			24.96	4.7	2.47	[illegible]	1507	.65	[illegible]	.69
255			31.28	[illegible]	1.23	[illegible]	[illegible]	.61	[illegible]	.69
256			36.79	8.42	.64	[illegible]	[illegible]	.3	.61	.74

Cavitation Limits (Speed Tests)

1.50 Prop.

$$\sigma = \frac{H_{IS} - H_{VAP}}{V_I^2/2g}$$

$$H_{IS} = H_{ATM} + \Delta PSI\left(\frac{144}{62.4}\right) + .75'$$

$$H_{ATM} = 32.12'$$

$$H_{IS} = 32.12 + 2.308\Delta PSI + .75 = 32.87 + 2.308\Delta PSI$$

$$H_{VAP} = 1.00'$$

$$\frac{V_I^2}{2g} = \left(\frac{Q}{A}\right)^2 \frac{1}{2g} = \frac{Q^2}{(.0434)^2(2)(32.2)} = .0143Q^2$$

$$\sigma = \frac{32.87 + 2.308\Delta PSI - 1}{.0143\,Q^2} = \frac{31.87 + 2.308\Delta PSI}{.0143Q^2}$$

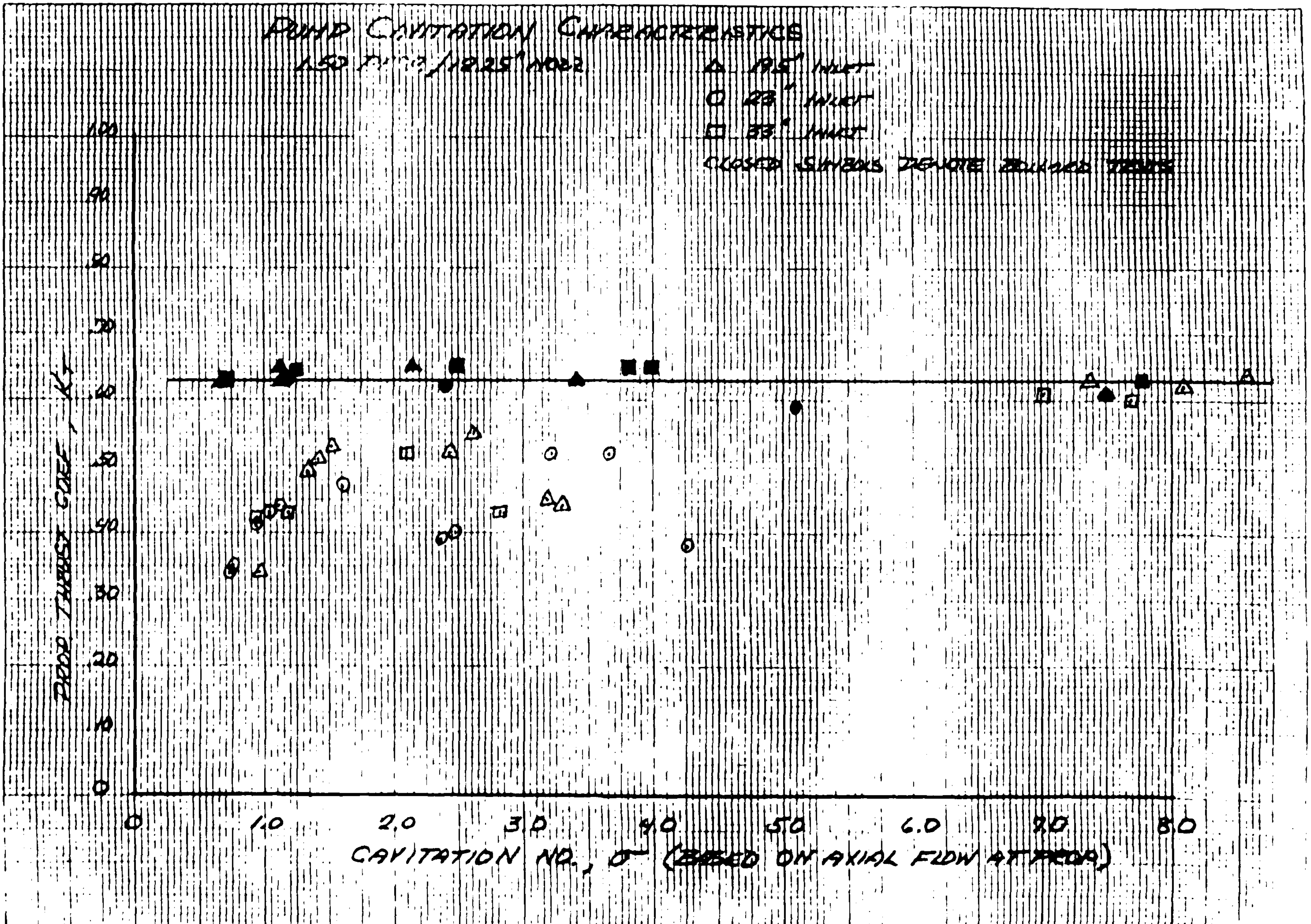
$$K_T = \frac{T_S}{\rho n^2 D^4} = \frac{T_S}{(1.94)\left(\frac{N}{60}\right)^2\left(\frac{[illegible]}{12}\right)^4} = 1002\frac{T_S}{N^2}$$

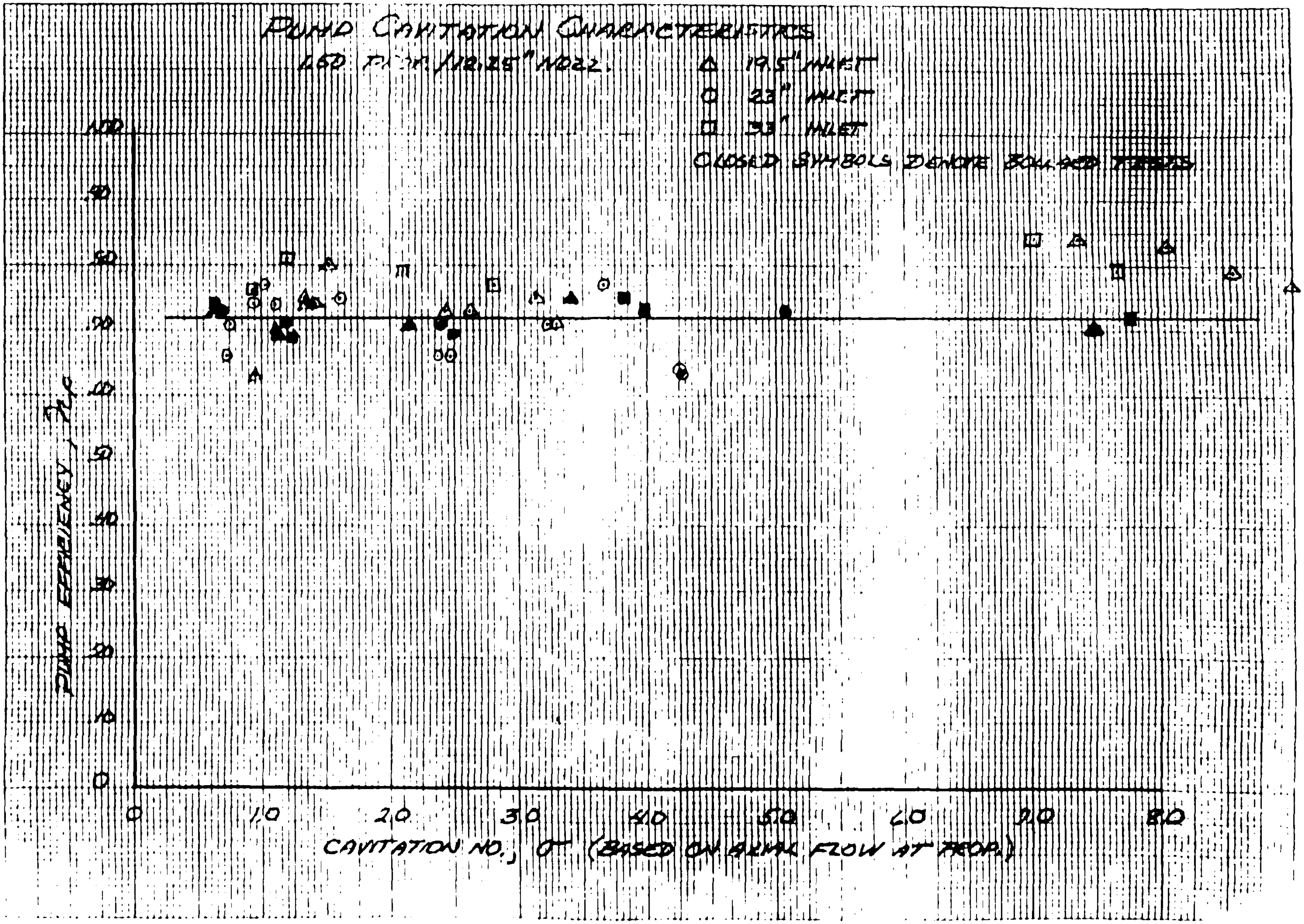
Run	No.	Inlet	Q	ΔPSI	σ	T_S	N	K_T	[illegible]	[illegible]
201	12.25	23'	16.06	+2.[illegible]	7.92	[illegible]	848	.41	.89	.63
202		0	32.9[illegible]	-2.99	1.61	1403	1923	.47	.90	.75
203			40.35	-4.29	.94	[illegible]	2101	.41	.90	.74
204			40.27	-3.53	1.03	[illegible]	2092	.43	.90	.77
205			42.05	-5.52	.76	[illegible]	[illegible]	.35	.83	.71
206			27.48	+1.24	3.22	[illegible]	[illegible]	[illegible]	.87	[illegible]
207			29.40	+6.06	3.00	[illegible]	[illegible]	.72	.89	.77
208			26.20	-3.30	[illegible]	[illegible]	[illegible]	.40	.88	[illegible]
209			26.[illegible]	-3.44	2.27	[illegible]	[illegible]	.57	.89	[illegible]
210			21.02	-2.14	4.26	[illegible]	1129	[illegible]	.89	[illegible]
211			20.77	-2.16	4.27	400	[illegible]	[illegible]	.89	.83
218			9.25	-.43	[illegible]	[illegible]	425	.78	.88	.73
219			[illegible]	-4.45	1.11	[illegible]	[illegible]	.84	.88	.74
220			4.00	-6.24	.73	941	[illegible]	.74	.80	—

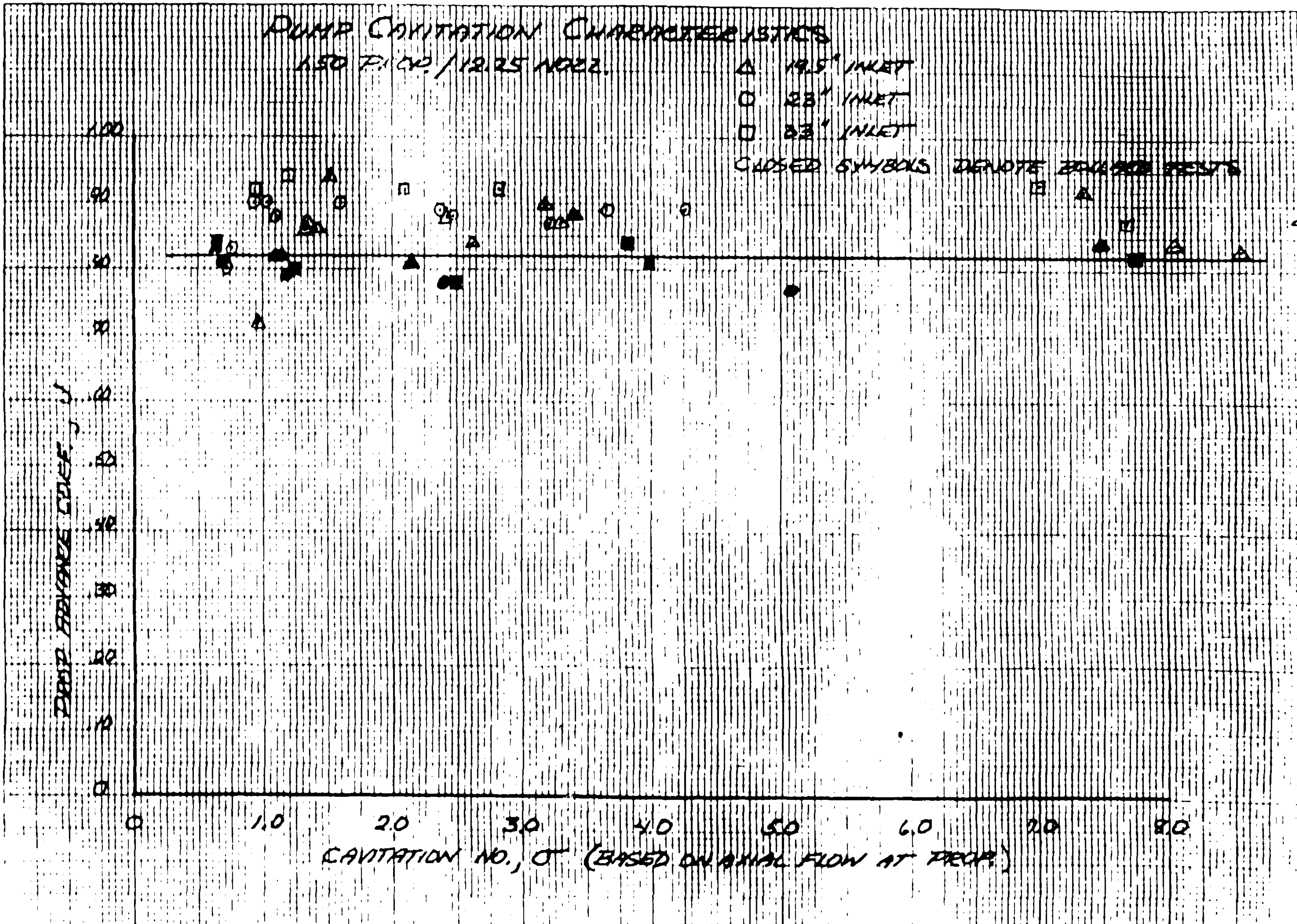
Cavitation Limits (Speed Tests)

1.5D Prop (Cont.)

Run #	Noz	Inlet	Q	ΔPSI	T	T_2	N	K_T	J	η_P
221	12.25"	19.5°	10.37	-.36	20.18		[illegible]10	.54	.80	.36
222		Δ	16.06	-.69	8.08		892	.62	.54	.3
223			15.54	-.99	8.57		863	.54	.83	.79
224			33.81	-3.34	1.42		1849	.51	.86	.34
225			34.38	4.02	1.34		1873	.49	.80	.35
226			26.18	-2.68	2.62		1458	.55	.64	.33
227			23.39	2.61	3.30		1252	.44	.87	.71
234			11.71	.48	15.69		643	.50	.65	.77
235			16.82	.69	7.37		862	.3	.92	.64
236			34.10	3.10	1.41		1875	.57	.86	.34
237			30.36	.14	2.32		520	.49	2.74	2.64
238			36.71	5.70	.76		2412	.34	.72	.63
239			33.74	3.09	1.52		1678	.53	.94	.80
240			34.62	3.78	1.35		1872	.49	.87	.34
241			[illegible]	3.[illegible]	2.43		[illegible]76	.52	.88	.73
242			23.74	[illegible]	3.18		[illegible]	.45	.70	.35
243			4.79	1.25	9.02		395	.49	.68	.77
244	12.25	33"	12.72	.61	14.74		[illegible]	.51	[illegible]	.78
245			17.05	1.16	7.02		[illegible]	[illegible]	.73	[illegible]
246			16.27	1.19	7.69		[illegible]	[illegible]	[illegible]	[illegible]
247			3[illegible]	3.11	1.19		[illegible]	.43	.94	.61
248			[illegible]	3.43	.74		[illegible]	.42	.92	[illegible]
249			27.27	2.44	2.[illegible]		[illegible]	[illegible]	.92	[illegible]
250			25.43	2.52	2.82		[illegible]	.43	.92	.77


PUMP CAVITATION CHARACTERISTICS
19.5" INLET
23" INLET
33" INLET
CLOSED SYMBOLS DENOTE
PROP THRUST COEF., K_T
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
CAVITATION NO., σ (BASED ON AXIAL FLOW AT PROP)


PUMP CAVITATION CHARACTERISTICS
LSD PUMP W/12.25" NOZZ.
△ 19.5" INLET
○ 23" INLET
□ 33" INLET
CLOSED SYMBOLS DENOTE SOLID TESTS
PUMP EFFICIENCY, η_p
CAVITATION NO., σ (BASED ON AXIAL FLOW AT PROP.)
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0


PUMP CAVITATION CHARACTERISTICS
1.50 P/D / 12.25 NOZZ.
△ 19.5" INLET
○ 28" INLET
□ 33" INLET
CLOSED SYMBOLS DENOTE
PROP ADVANCE COEF., J
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
CAVITATION NO., σ (BASED ON AXIAL FLOW AT PROP.)

VENTILATION (SPEED TESTS)

1.50 PROP

$$F_\nabla = \frac{V_0}{\sqrt{g\,\nabla^{1/3}}}$$

$$\nabla^{1/3} = \left(\frac{5802}{62.4}\right)^{1/3} = 4.53$$

$$F_\nabla = \frac{V_0}{\sqrt{(32.2)(4.53)}} = .0828\,V_0 = .1217\,V_{MPH}$$

$$K_T = \frac{T_S}{\rho n^2 D^4} = \frac{T_S}{(1.94)\left(\frac{N}{60}\right)^2\left(\frac{14}{12}\right)^4} = 1002\,\frac{T_S}{N^2}$$

$$K_{T_{BOLL}} = .63$$

RUN #	NOZZ	INLET	V_{MPH}	F_∇	T_S	N	K_T	$\frac{K_T}{K_{T_{BOLL}}}$
201	12.25	23	4.95	.60	273	848	.41	.65
202			17.20	2.14	1403	1723	.47	.75
203			25.[illegible]3	3.06	5[illegible]	2101	.41	.65
204			25.36	3.09	18[illegible]	2092	.43	[illegible]
205			26.23	3.[illegible]	4[illegible]	2[illegible]	.35	[illegible]
206			10.26	[illegible]	[illegible]	[illegible]	.52	.83
207			10.93	[illegible]3	[illegible]2	[illegible]	.52	.83
208			8.49	[illegible]3	[illegible]	[illegible]	.40	.63
209			9.40	[illegible]2	[illegible]	[illegible]	.39	.62
210			7.00	[illegible]	[illegible]	[illegible]	[illegible]	.60
211			7.23	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
218			2[illegible]	[illegible]3		[illegible]	.55	.72
219			22.31	[illegible]	16.6	[illegible]	[illegible]	.70
220			25.59	3[illegible]	19.41	[illegible]	[illegible]	[illegible]

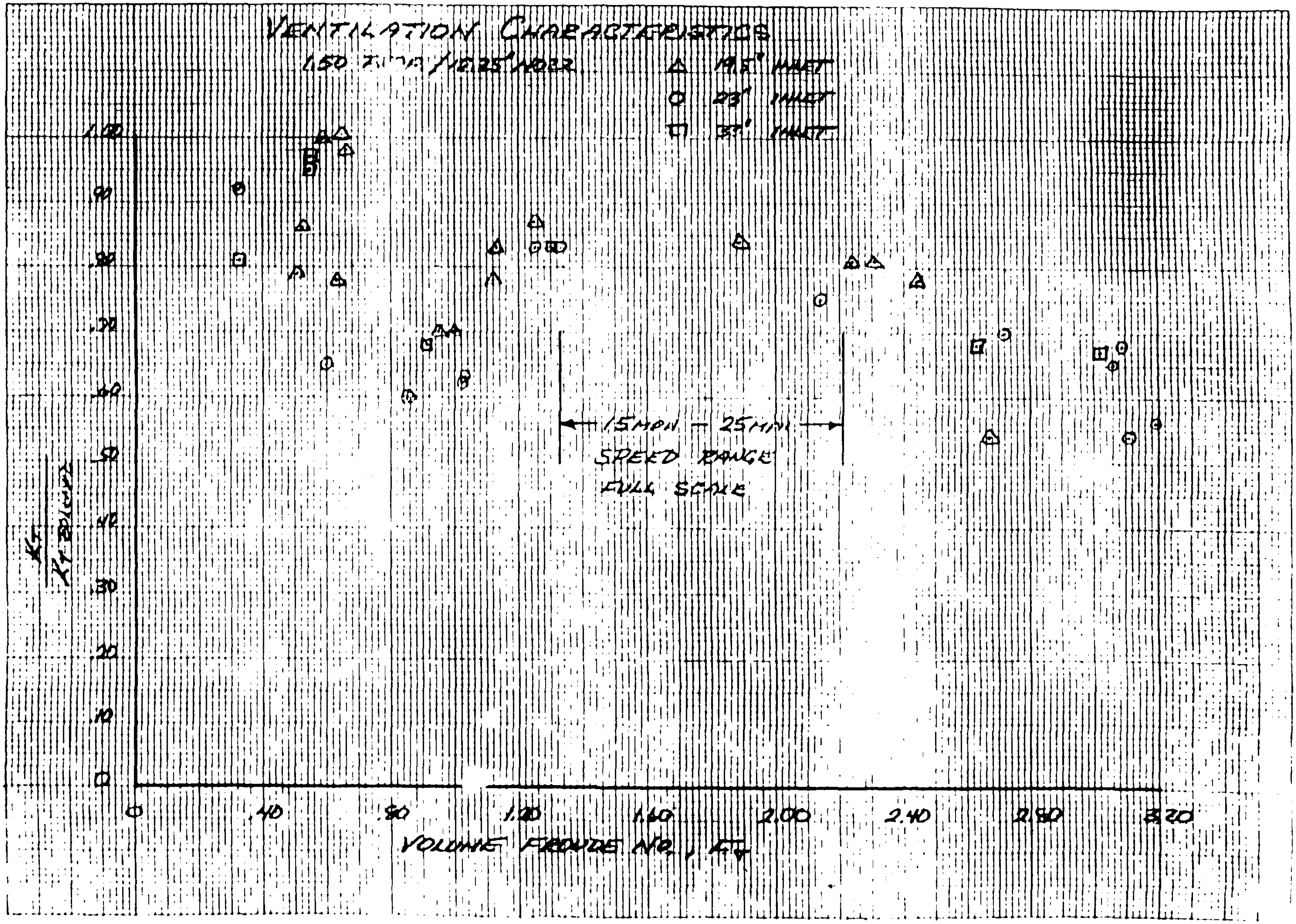
VENTILATION

1.50 PROP (CONT.)

RUN #	NOZZ	INLET	V_{max}	F_∇	T_s	N	K_T	$K_T/K_{T_{max}}$
221	12.25	9.5	4.28	.52		[illegible]	.54	.86
222			5.42	[illegible]		[illegible]	.62	.98
223			5.33	.65		683	.64	1.02
224			18.98	2.31		[illegible]	.57	.81
225			20.03	2.44		[illegible]	.49	.78
226			10.26	1.25		[illegible]	.55	.87
227			8.23	1.00		1257	.44	.70
234			4.22	.51		[illegible]	.50	.79
235			4.85	.59		[illegible]	.63	1.00
236			18.42	2.24		[illegible]	.51	.81
237			9.06	1.10		520	.49	.78
238			21.92	2.67		2412	.34	.54
239			15.51	1.89		1678	.53	84
240			20.05	2.44		[illegible]	.49	.78
241			9.25	1.13		[illegible]	.52	.83
242			9.81	.95		[illegible]	.45	.71
243			5.4	.63		[illegible]	.47	.78
244	12.25	33°	2.69	.33		632	.51	.81
245			[illegible]	.55		[illegible]	.61	.97
246			4.55	.55		[illegible]	.60	.95
247			21.59	2.63		[illegible]	[illegible]	.68
248			[illegible]	3.02		[illegible]	[illegible]	.67
249			[illegible]	1.30		[illegible]	[illegible]	.83
250			[illegible]	.91		[illegible]	[illegible]	.85

$$F_\nabla = \frac{1.47 V_{max}}{\sqrt{(32.2)(\text{[illegible]})}} = \text{[illegible]}\ V_{max}$$

V_{max}	F_∇
[illegible]	[illegible]
	.33
[illegible]	[illegible]
2[illegible]	2.21


VENTILATION CHARACTERISTICS
INLET
INLET
INLET
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
$\frac{K_T}{K_T \text{ BOLLARD}}$
15 MPH — 25 MPH
SPEED RANGE
FULL SCALE
0
.40
.80
1.20
1.60
2.00
2.40
2.80
3.20
VOLUME FROUDE NO., F_∇

APPENDIX D

ESTIMATED INLET LOSSES

SUMMARY

ENTRANCE	1.5825'
INTAKE FRICTION + BEND	1.0149
SHAFT	.4207
TRANSITION	.9402
BEARING TUBE (FRICTION)	.0384
BEARING TUBE (FRONTAL)	.2079
STRUTS (PROFILE)	.1246
STRUTS (INTERFERENCE)	.0060

$$HL_I = 4.3352'$$

$$k = \frac{HL_I}{Q^2} = \frac{4.3352}{(40)^2} = .0027$$

$$HL_I = .0027\,Q^2$$

ESTIMATED INLET LOSSES

ENTRANCE

Q = NOM. FLOW RATE = 40 FT^3/SEC

A = ENTRANCE AREA = $(14)(19.5)/144 = 1.90$ FT^2

V = ENTRANCE VELOCITY = $\frac{Q}{A} = \frac{40}{1.90} = 21.05$ FT/SEC

K = LOSS COEF. = .23

$HL = \frac{KV^2}{2g} = \frac{(.23)(21.05)^2}{2(32.2)} = 1.5825'$

INTAKE FRICTION + BEND

Q = 40 FT^3/SEC.

A = INLET AREA = $(14)(14)/144 = 1.36$ FT^2

V = INLET VELOCITY = $Q/A = 40/1.36 = 29.41$ FT/SEC.

d_e = EQUIV. INLET DIAM = $\frac{4A}{2(14+14)/12} = \frac{4(1.36)\,12}{2(14+14)} = 1.17'$

$R_e = \frac{Vd_e}{1.24 \times 10^{-5}} = \frac{(29.41)(1.17)}{1.24 \times 10^{-5}} = 2.77 \times 10^6$

e = ROUGHNESS = .000005' (SIM TO DRAWN TUBING)

e/d_e = .000005/1.17 = .00000427

f = FRICTION FACTOR = .0099

L_I = INTAKE LENGTH = $11/12 = .92'$

L_B = EQUIV. LENGTH OF BEND = $\left(\frac{L}{D}\right)_B d_e \left(\frac{K}{90}\right) = (16)(1.17)\left(\frac{38.5}{90}\right) = 8.01$

L = TOT. EQUIV. LENGTH = $L_I + L_B = .92 + 8.01 = 8.93'$

$HL = f\left(\frac{L}{d_e}\right)\left(\frac{V^2}{2g}\right) = .0099\left(\frac{8.93}{1.17}\right)\frac{(29.41)^2}{2(32.2)} = 1.0149'$

ESTIMATED INLET LOSSES

SHAFT

C_D = DRAG COEF. DUE TO CROSS FLOW = $1.1 \sin^3 \alpha = 1.1 \sin^3 36° = .24$

V = INLET VELOCITY = 69.41 FT/SEC

l = SHAFT LENGTH ... = 1.42'

d = SHAFT DIAM = 1.5/12 = .125'

D = SHAFT DRAG = $C_D \rho_2 V^2 l d$ = (.24)(1.94/2)(69.41)^2(1.42)(.125) = 35.24#

$h_L = \frac{D}{\rho g A}$ = $\frac{35.24}{(1.94)(32.2)(1.34)}$ = .4207'

TRANSITION

Q = 40 FT³/SEC

A = AREA AT SMALL END = (.96)(.785)(14.12)²/144 = 1.0434 FT²

V = VELOCITY AT SMALL END = Q/A = 40/1.0434 = 38.31 FT/SEC

[illegible]

[illegible] = .0412

$h_L = K \frac{V^2}{2g}$ = (.0412)(38.31)²/2(32.2) = .9392

BEARING TUBE (CENTER)

V = 38.31 FT/SEC

l = TUBE LENGTH = [illegible]

$R_e = \frac{Vl}{1.22 \times 10^{-5}}$ = [illegible]

C_f = .00385

S = TUBE WETTED SURF = [illegible] = .17 [illegible]

D = TUBE DRAG = C_f ... = (.00385)(...)(1.94/2)(38.31)² = 3.95#

$h_L = \frac{D}{\rho g A}$ = [illegible] = .0784

ESTIMATED INLET LOSSES

BEARING TUBE (FRONTAL)

$A_0 = (.385)(2^2 - 1.5^2)/144 = .0095 \text{ FT}^2$

$V = 38.34 \text{ FT/SEC}$

$C_D = 1.00$

$D = C_D A_0 \rho/2 V^2 = (1.00)(.0095)(\frac{1.94}{2})(38.34)^2 = 13.55^{\#}$

$HL = \dfrac{D}{\rho g A} = \dfrac{13.55}{(1.94)(32.2)(1.0434)} = .2079'$

STRUTS (PROFILE)

$A = 1.0434 \text{ FT}^2$

$V = 38.34 \text{ FT/SEC}$

c = STRUT CHORD = $3'' = .25'$

$Re = \dfrac{Vc}{1.211 \times 10^{-5}} = \dfrac{(38.34)(.25)}{1.211 \times 10^{-5}} = 7.73 \times 10^5$

$C_f = .0046$

$t/c = .3125/3 = .1042$

$C_D = 2C_f (1 + 1.2\, t/c) = 2(.0046)(1 + 1.2 \times .1042) = .0122$

S = STRUT PLANFORM AREA = $.4667 \text{ FT}^2$

D = STRUT DRAG = $C_D S \rho/2 V^2 = (.0122)(.4667)(\frac{1.94}{2})(38.34)^2 = 8.12^{\#}$

$HL = \dfrac{D}{\rho g A} = \dfrac{8.12}{(1.94)(32.2)(1.0434)} = .1246'$

ESTIMATED INLET LOSSES

STRUT (INTERFERENCE)

$A = 1.0434 \text{ ft}^2$

$V = 38.34 \text{ ft/sec}$

t = [illegible] .3125" = .0260' $t/c = .1042$

$C_D = .75\, t/c - \dfrac{.0003}{(t/c)^2} = (.75)(.1042) - \dfrac{.0003}{(.1042)^2} = .0505$

D = [illegible] $= .3821$

$HL = \dfrac{D}{\rho g A} = \dfrac{.382}{[illegible]} = .0060'$

ESTIMATED CASING LOSS

CASING

$Q = 40 \text{ ft}^3/\text{sec}$

$A = \text{CASING AREA} = .785\left(\frac{14.12}{12}\right)^2 = 1.087 \text{ ft}^2$

$V = Q/A = 40/1.087 = 36.80 \text{ ft/sec}$

$d = \text{CASING DIAM.} = 14.12 = 1.1767'$

$R_e = \frac{Vd}{1.24 \times 10^{-5}} = \frac{(36.80)(1.1767)}{1.24 \times 10^{-5}} = 3.49 \times 10^6$

$e = .000005'$

$e/d = .000005/1.1767 = .00000425$

$f = .0097$

$L = \text{CASING LENGTH} = 1.33'$

$HL = f\left(\frac{L}{d}\right)\frac{V^2}{2g} = (.0097)\left(\frac{1.33}{1.177}\right)\frac{(36.80)^2}{2(32.2)} = .2319'$

$k = \frac{HL}{Q^2} = \frac{.2319}{(40)^2} = .000145$

$HL = .000145\, Q^2$

ESTIMATED NOZZLE LOSS

$$HL_j = \frac{V_j^2}{2g}(1+K)$$

$$V_j = Q/A_j$$

$$Q = 40\ FT^3/SEC$$

$$A_j = .785\ d_j^2$$

$$d_j = D\left(\frac{d_j}{D}\right)$$

$$\frac{d_j}{D} = f\left(\frac{d}{D}\right)$$

$$d = 12.00''$$

$$D = 14.12''$$

$$\frac{d}{D} = \frac{12.00}{14.12} = .8499$$

$$\frac{d_j}{D} = .805$$

$$d_j = (14.12)(.805) = 11.37'' = .9472'$$

$$A_j = (.785)(.9472)^2 = .7043\ FT^2$$

$$V_j = 40/.7043 = 56.79\ FT/SEC$$

$$K = f\left(\frac{a}{A}\right)$$

$$a = .785\,d^2 = .785(12)^2 = 113.04\ in^2 = .785\ FT^2$$

$$A = .785\,D^2 = .785(14.12)^2 = 156.51\ in^2 = 1.087\ FT^2$$

$$\frac{a}{A} = \frac{.785}{1.087} = .7222$$

$$K = .042$$

$$HL_j = \frac{(56.79)^2}{2(32.2)}(1+.042) = 52.18'$$

$$k = \frac{HL}{Q^2} = \frac{52.18}{(40)^2} = .0328$$

$$HL_j = .0328\ Q^2$$

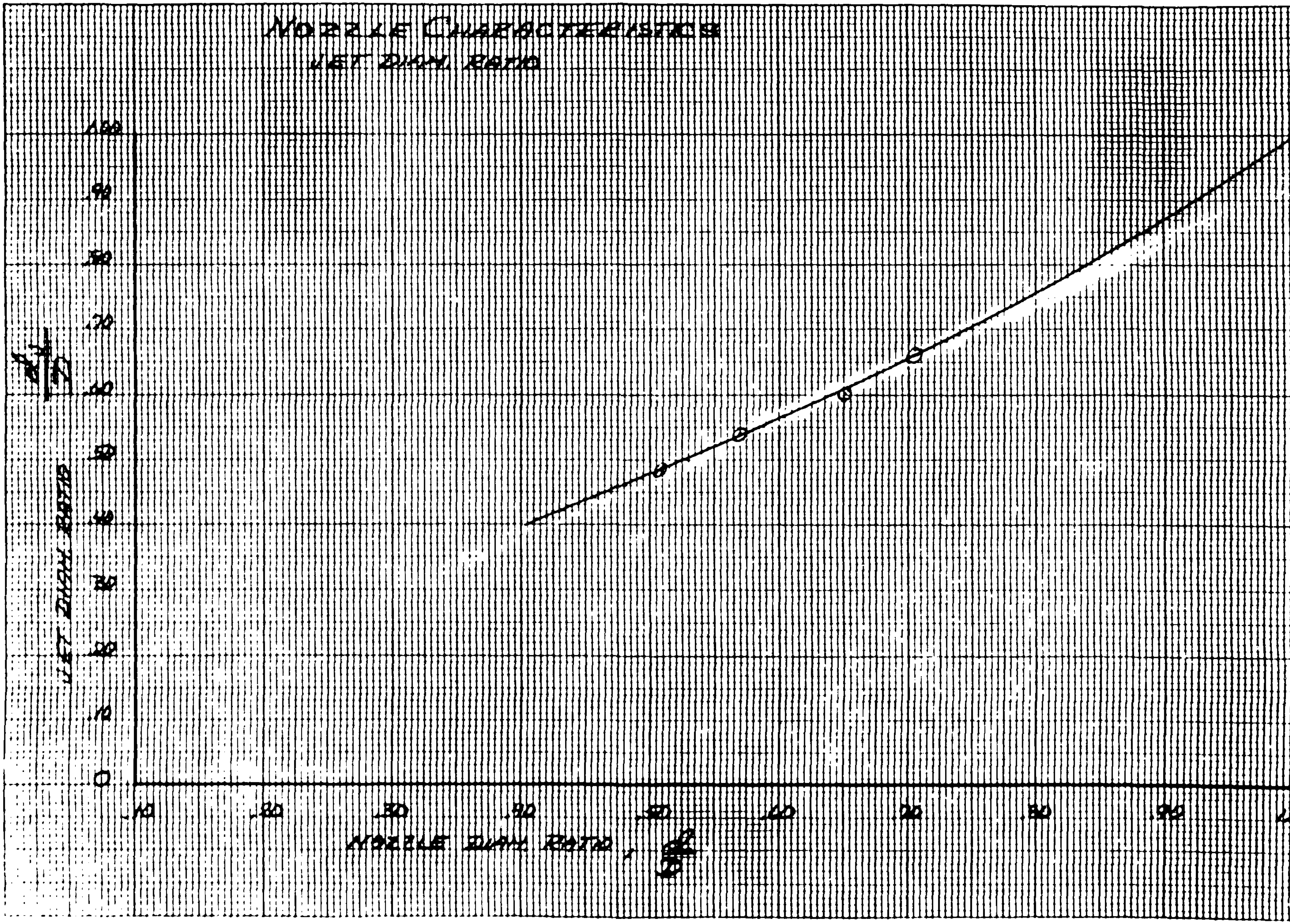
NOZZLE CHARACTERISTICS

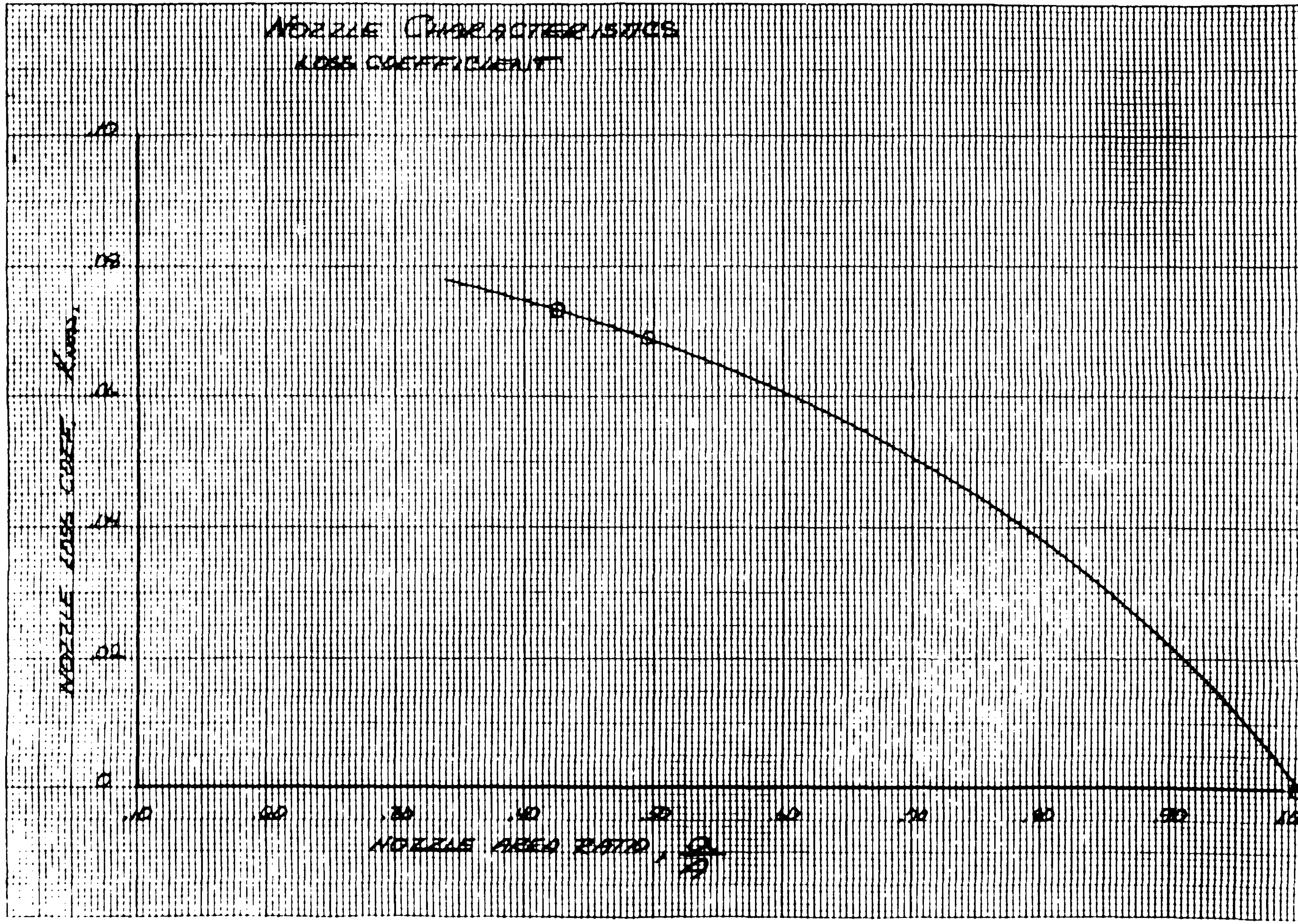
JET DIAM.

NOZZ #	$\frac{d}{D}$	$\frac{d_i}{D}$
1	.5081	.4643
2	.5686	.5455
3	.6508	.6032
4	.7027	.6575
None	1.00	1.00

LOSS COEF.

NOZZ #	$\frac{d}{D}$	$\frac{a}{A}$	K
3	.6508	.4245	.0733
4	.7027	.4940	.0688
None	1.00	1.00	0


NOZZLE CHARACTERISTICS
JET DIAM RATIO
JET DIAM RATIO
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
NOZZLE DIAM RATIO


NOZZLE CHARACTERISTICS
LOSS COEFFICIENT
NOZZLE LOSS COEFF.
NOZZLE AREA RATIO
.10
.08
.06
.04
.02
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00

ESTIMATED INLET PRESSURE RECOVERY

$$H_o = RPR \frac{V_o^2}{2g}$$

$$RPR = 1.00$$

$$H_o = (1.00) \frac{V_o^2}{2(32.2)} = .0155 V_o^2$$

AD-A153 266 DESIGN PROCEDURES FOR LOW SPEED WATERJETS SUITABLE FOR APPLICATION IN AMP..(U) STEVENS INST OF TECH HOBOKEN NJ DAVIDSON LAB J K ROPER MAR 85 SIT-DL-85-9-2518 2/2

UNCLASSIFIED N00014-83-C-0780 F/G 21/7 NL

END

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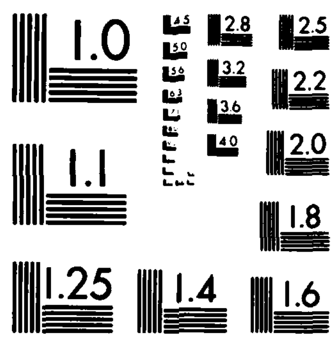


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Estimated Pump Head Required

$$H_{P\,REQ} = HL_I + HL_C + HL_J - H_o$$

$$HL_I = .0027\,Q^2$$

$$HL_C = .000145\,Q^2$$

$$HL_J = .0328\,Q^2$$

$$H_o = .0155\,V_o^2$$

$$H_{P\,REQ} = (.0027 + .000145 + .0328)\,Q^2 - .0155\,V_o^2$$

$$= .0356\,Q^2 - .0155\,V_o^2$$

ESTIMATED CAVITATION LIMITS

$$\sigma = \frac{H_{I_s} - H_{vap}}{V_I^2/2g}$$

$$H_{I_s} = H_{atm} + H_0 - H_{L_I} - \frac{V_I^2}{2g}$$

$$H_{atm} = 33.07'$$

$$H_0 = .0155 V_0^2$$

$$H_{L_I} = .0027 Q^2$$

$$\frac{V_I^2}{2g} = \frac{Q^2}{(1.0434)^2} \frac{1}{2(32.2)} = .0143 Q^2$$

$$H_{I_s} = 33.07 + .0155 V_0^2 - .0027 Q^2 - .0143 Q^2$$

$$= 33.07 + .0155 V_0^2 - .017 Q^2$$

$$H_{vap} = 1.00'$$

$$\sigma = \frac{33.07 + .0155 V_0^2 - .017 Q^2 - 1}{.0143 Q^2} = \frac{32.07 + .0155 V_0^2 - .017 Q^2}{.0143 Q^2}$$

$$.0143 Q^2 \sigma + .017 Q^2 = 32.07 + .0155 V_0^2$$

$$Q^2 = \frac{32.07 + .0155 V_0^2}{.0143 \sigma + .017}$$

SUGGESTED $\sigma_{min} = .25$

ESTIMATED PROPELLER CHARACTERISTICS

PUMP EFFICIENCY (1.50 PROP / 12.25 NOZZ)

ESTIMATED FROM CURVES OF η_p - VS - σ AND η_p - VS - SHP

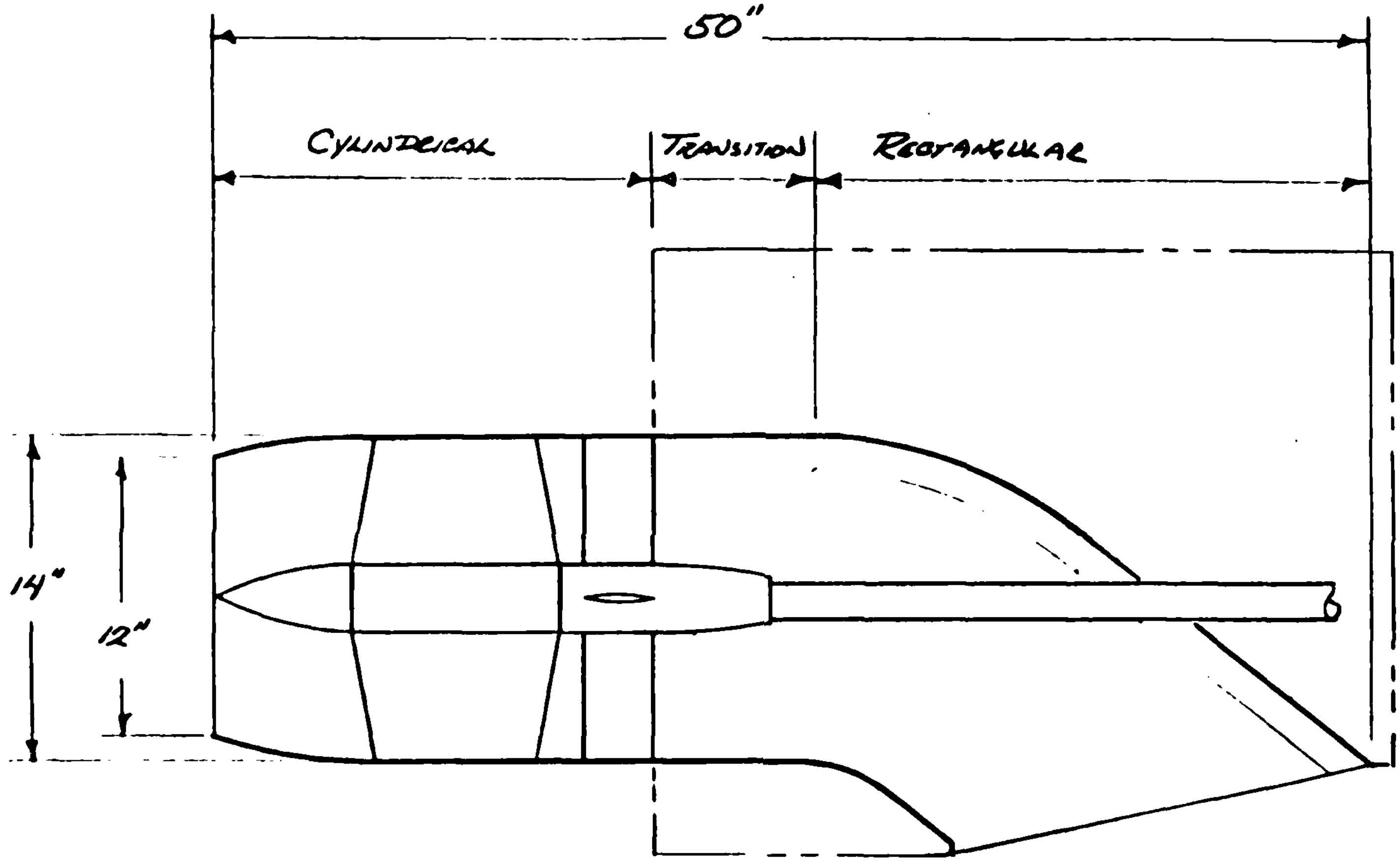
USE $\eta_p = .72$

PROP. ADVANCE COEF (1.50 PROP / 12.25 NOZZ)

ESTIMATED FROM CURVES OF J - VS - σ AND J - VS - SHP

USE $J = .82$

APPENDIX E



14" PUMP
INSTALLED IN .55 SCALE MODEL

SHP REQUIRED

CALCULATION NOTES

V_{MPH} = CRAFT SPEED ~ MPH (NOMINAL VALUES)

V_0 = $1.47 (V_{MPH})$

Q = FLOW RATE ~ FT^3/SEC (NOMINAL VALUES)

H_p = REQD. PUMP HEAD = $.0356\, Q^2 - .0155\, V_0^2$

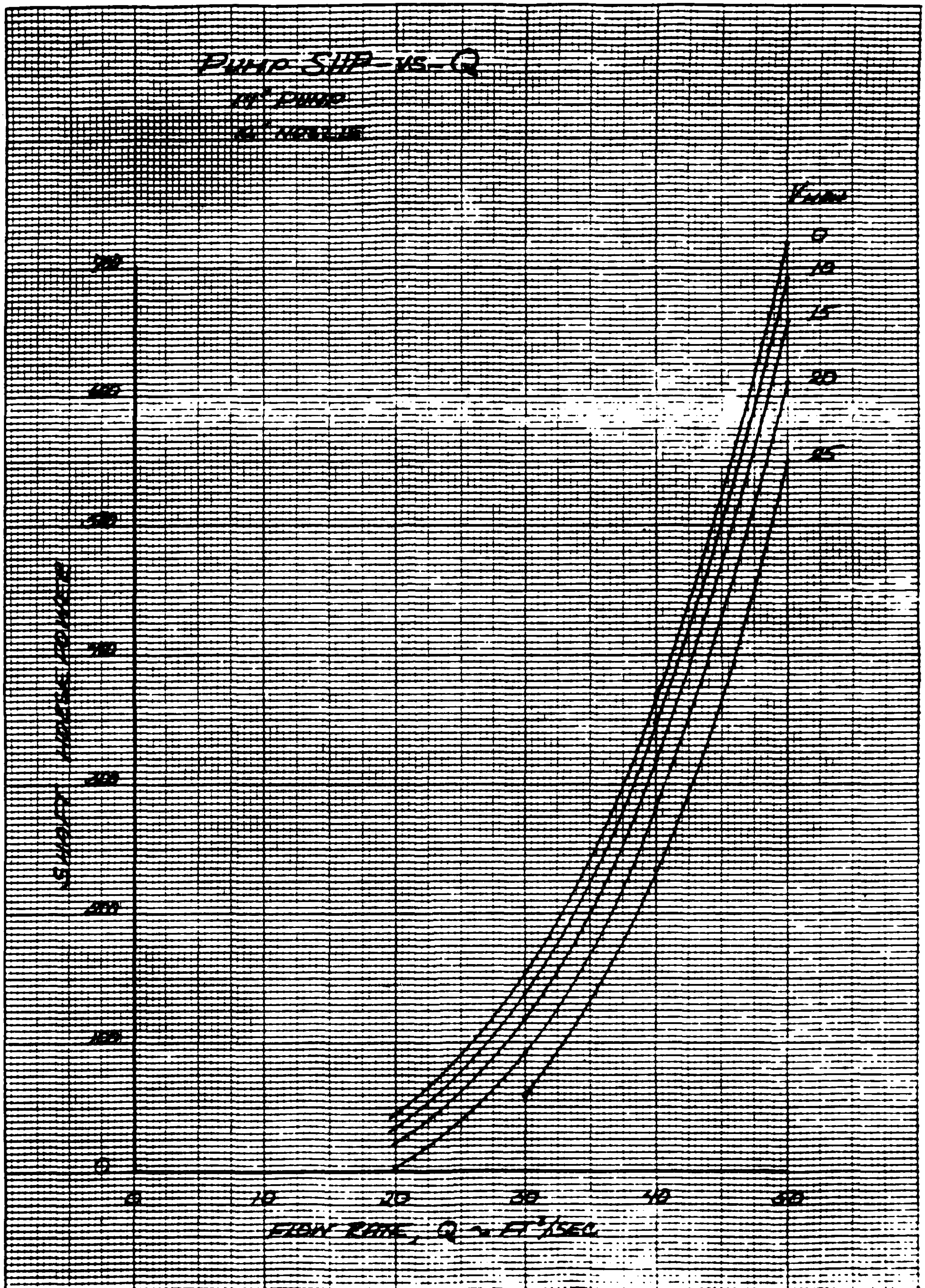
η_p = PUMP EFFICIENCY = .92

SHP = POWER REQD. BY PUMP = $\dfrac{\rho g Q H_p}{550\, \eta_p}$

SHP REQUIRED

CALCULATION

V_{MPH}	V_0	Q	H_p	η_p	SHP
0	0	20	17.24	.72	46
		30	32.74		155
		40	56.96		366
		50	89.00		719
10	14.70	20	10.89	.72	35
		30	28.[illegible]		139
		40	53.61		347
		50	85.66		692
15	22.05	20	6.70	.72	22
		30	24.50		119
		40	49.42		317
		50	81.46		658
20	29.40	20	.84	.72	3
		30	18.64		91
		40	43.56		282
		50	75.60		611
25	36.75	20	-6.69	.72	—
		30	11.11		54
		40	36.03		233
		50	68.07		550


PUMP SHP -VS- Q
SHAFT HORSE POWER
FLOW RATE, Q ~ FT³/SEC
0
10
15
20
25
0
10
20
30
40
50

SYSTEM PERFORMANCE (POWER LIMIT)

CALCULATION NOTES

V_{MPH} = CRAFT SPEED ~ MPH (NOMINAL VALUES)

V_0 = $1.47\ V_{MPH}$

SHP = POWER TO PUMP ~ HP (NOMINAL VALUES)

Q = FLOW RATE ~ FT^3/SEC (FROM SHP CORR. CURVES)

A_J = JET AREA ~ FT^2

V_J = JET VELOCITY = $\frac{Q}{A}$

T_J = JET THRUST = $\rho Q (V_J - V_0)$

OPC = PROPULSIVE COEF. = $\frac{T_J V_0}{550\ SHP}$

J = PROP ADVANCE COEF. = .82

N = PROP RPM = $49.29\ \frac{Q}{J}$

SYSTEM PERFORMANCE (POWER LIMIT)

CALCULATION

V_{KTS}	V_0	SHP	Q	A_J	V_J	T_J	OPC	J	N
0	0	100	25.8	.7043	36.63	1838	—	.82	1551
		150	29.7		42.17	2489	—		1795
		200	32.9		46.71	3054	—		1978
		250	35.4		50.26	3536	—		2128
		300	37.6		53.39	3990	—		2260
10	14.70	100	27.1		38.48	1281	.342	.82	1629
		150	30.8		43.73	1777	.317		1851
		200	33.8		47.99	2236	.299		2032
		250	36.3		51.54	2658	.284		2182
		300	38.4		54.52	3039	.271		2308
15	25.35	100	28.6		40.61	1055	.423	.82	1719
		150	32.2		45.72	1515	.405		1936
		200	35.1		49.84	1939	.389		2110
		250	37.4		53.10	2308	.370		2248
		300	39.4		55.94	2654	.355		2368
20	29.41	100	30.7		43.59	866	.463	.82	1845
		150	34.0		48.27	1275	.454		2044
		200	36.7		52.11	1657	.443		2206
		250	38.8		55.09	1981	.424		2332
		300	40.7		57.79	2297	.409		2446
25	[illegible]	100	33.0		46.66	663	.443	.82	1484
		150	[illegible]		51.11	1027	.456		2164
		200	38.6		54.81	[illegible]	[illegible]		2320
		250	40.8		57.93	[illegible]	[illegible]		2452
		300	42.8		60.77	2043	[illegible]		2573

SYSTEM PERFORMANCE (CAVITATION LIMITS)

CALCULATION NOTES

σ = CAVITATION INDEX, BASED ON INLET AXIAL FLOW (SELECTED VALUES)

V_{mph} = CRAFT SPEED ~ MPH (NOMINAL VALUES)

V_0 = $1.47\ V_{mph}$

Q = FLOW RATE = $\dfrac{32.07 + .0155 V_0^2}{.0143\sigma + .017}$

A_J = JET AREA ~ FT^2

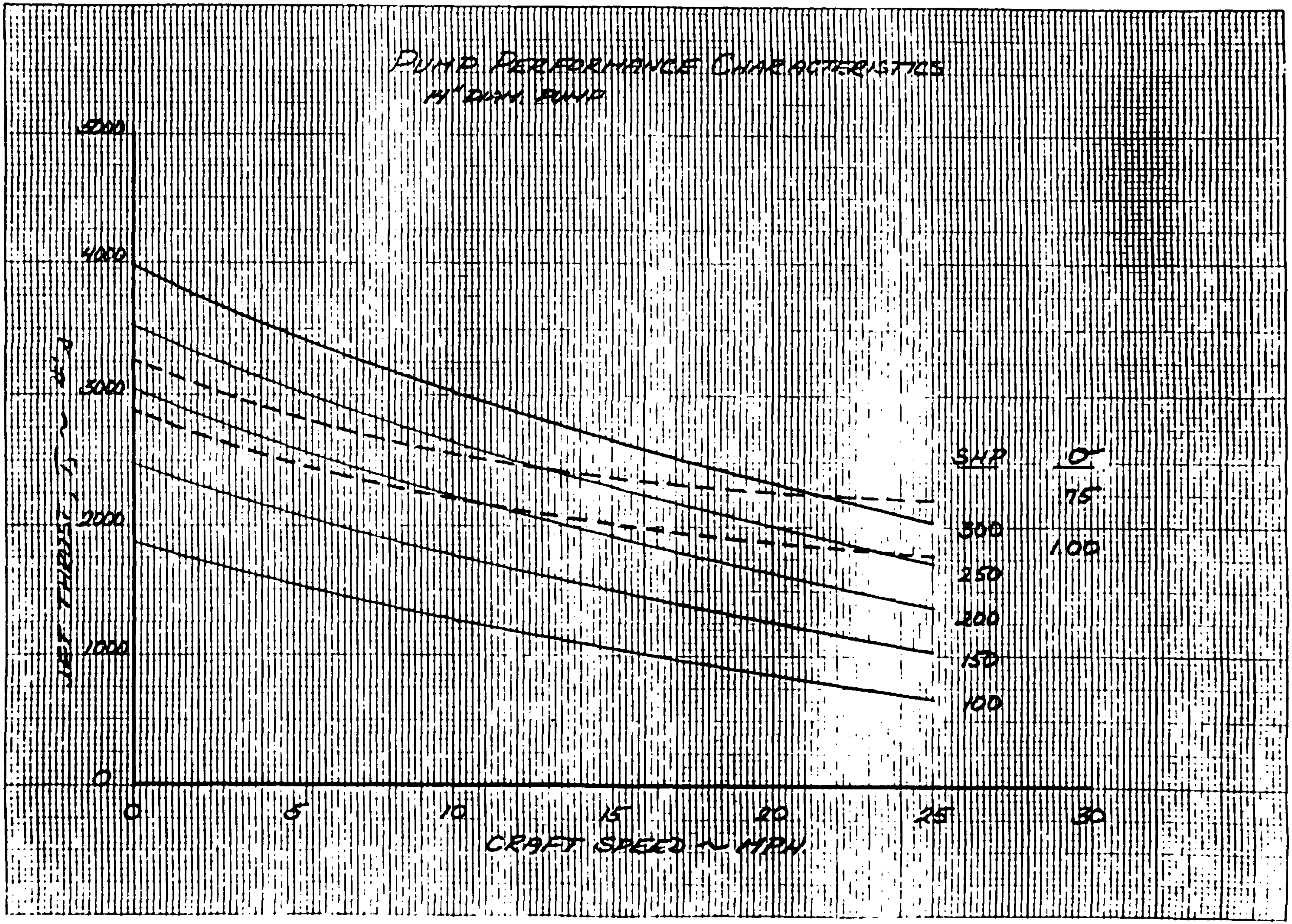
V_J = JET VELOCITY = $\dfrac{Q}{A_J}$

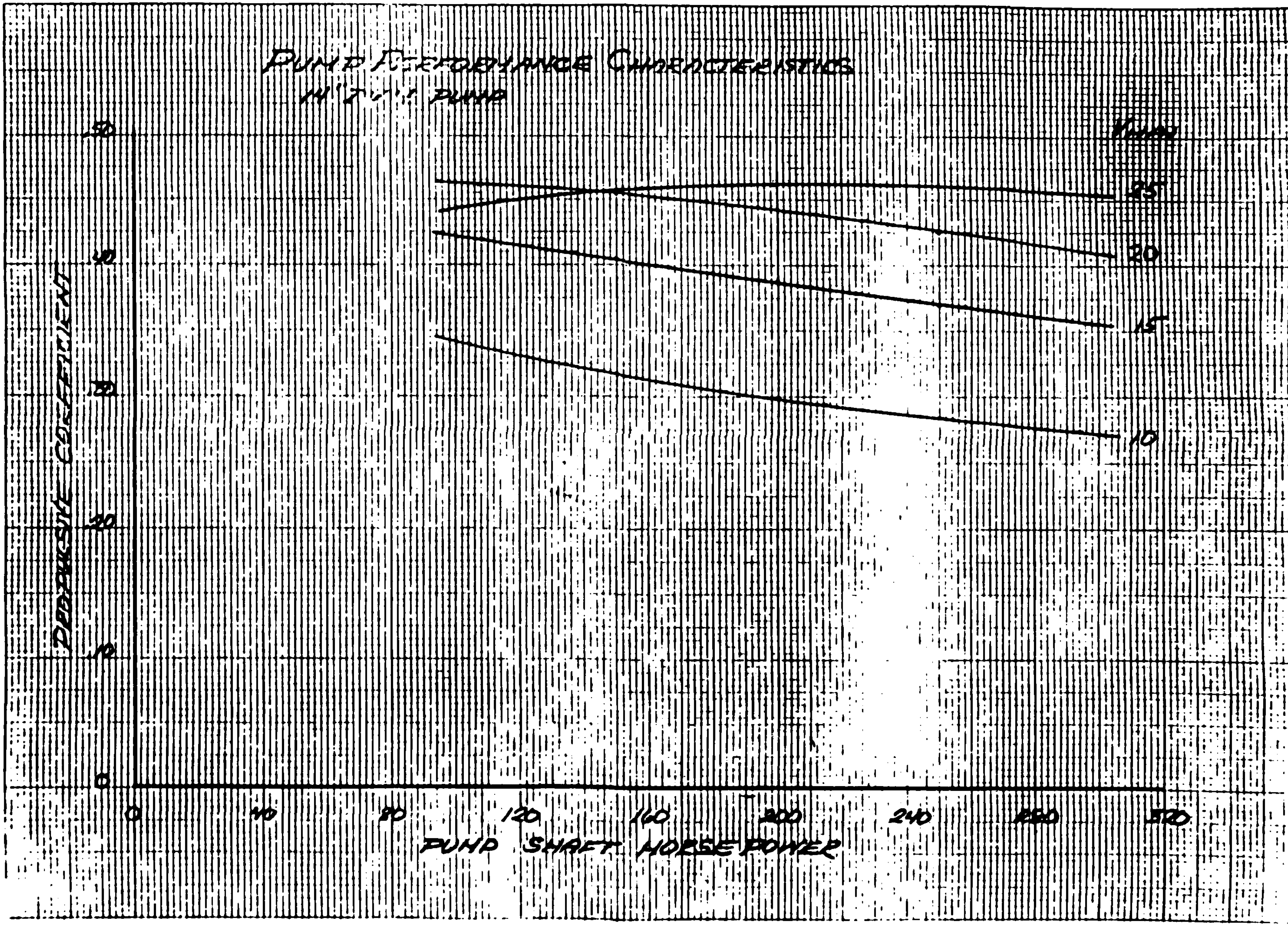
T_J = JET THRUST = $\rho Q (V_J - V_0)$

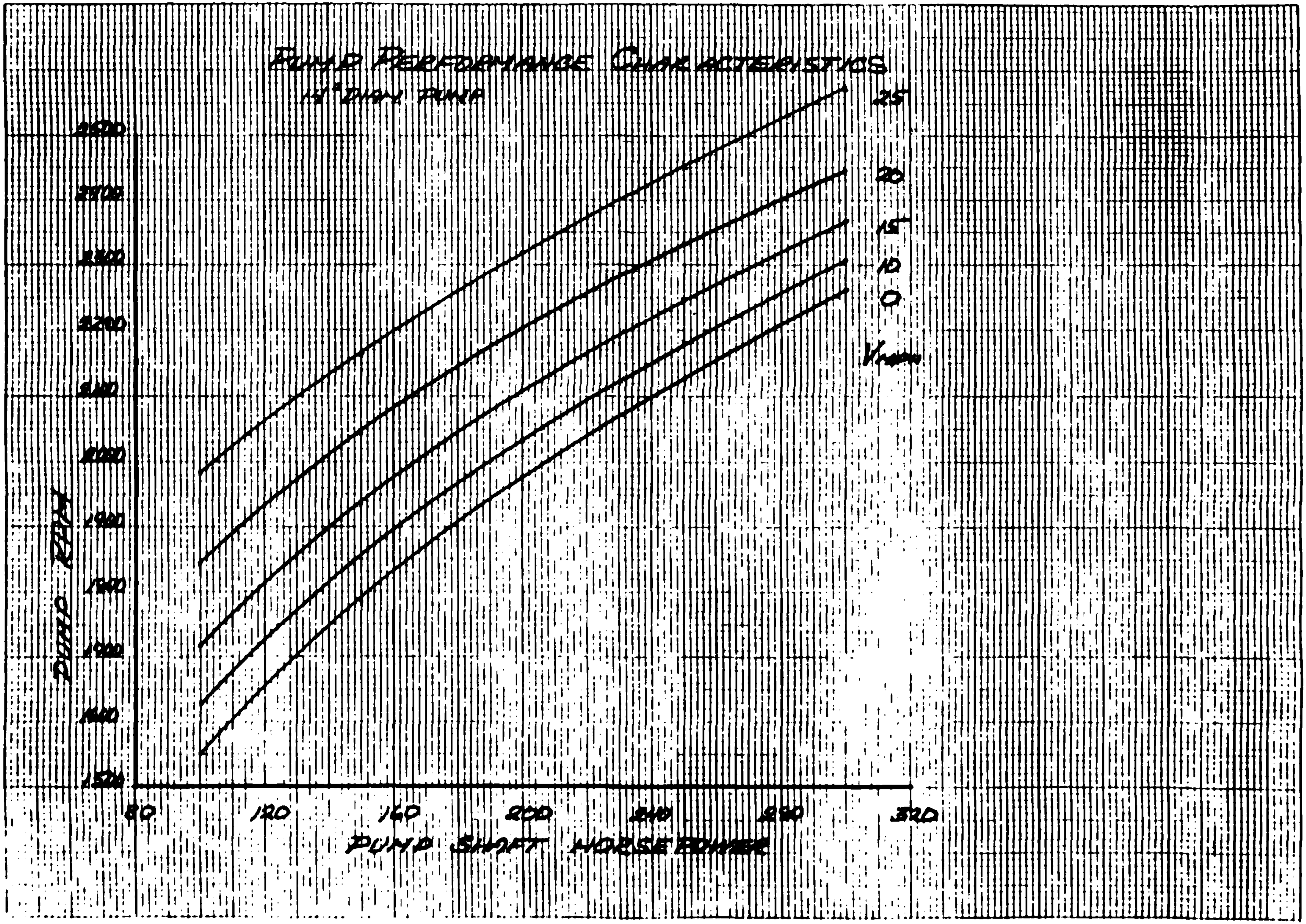
System Performance (Cavitation Limit)

Calculation

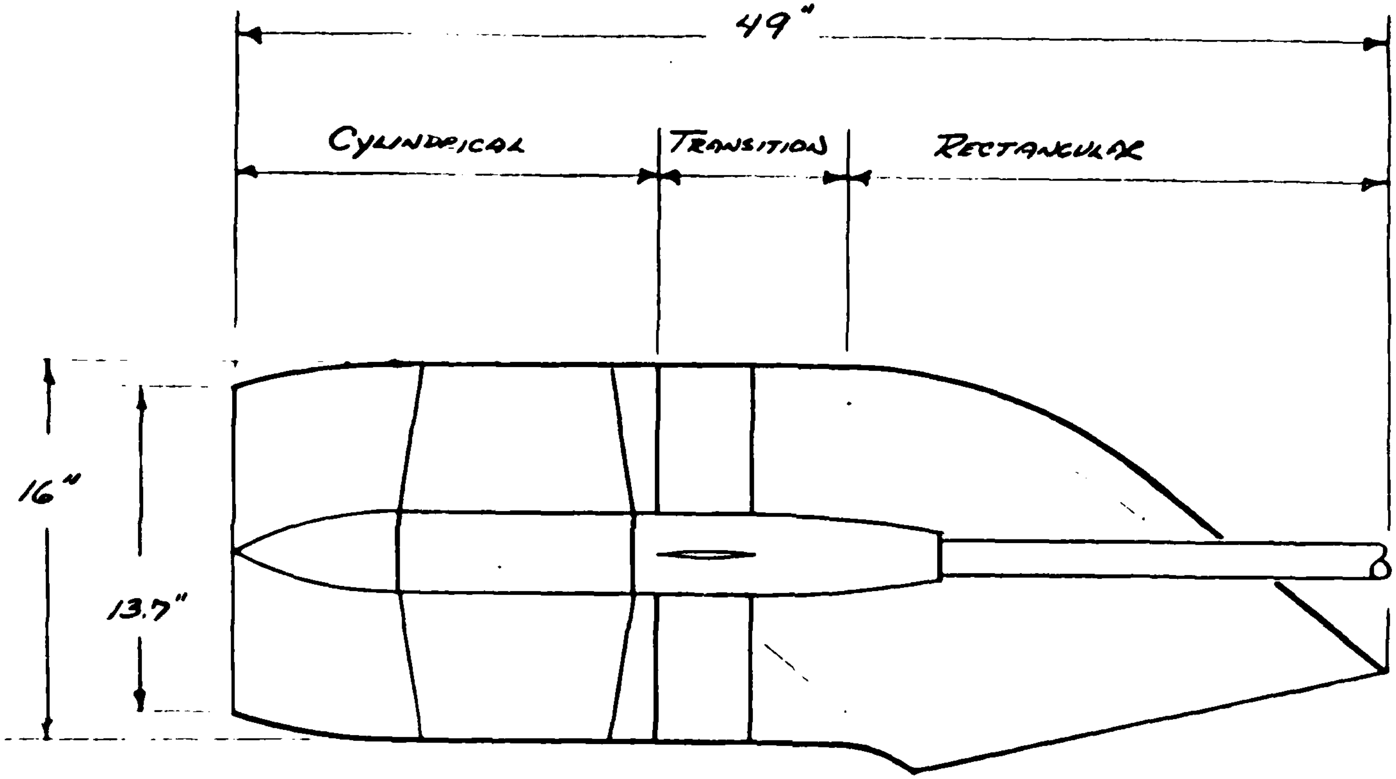
σ	V_{MPH}	V_0	Q	A_j	V_j	T
1.00	0	0	32.01	.7043	45.45	2892
	10	14.70	33.64		47.76	2210
	15	22.05	35.57		50.57	2012
	20	29.40	38.11		54.12	1872
	25	36.75	41.15		58.43	1773
.75	0	0	34.01	.7043	48.29	3264
	10	14.70	35.74		50.25	2561
	15	22.05	37.80		53.66	2375
	20	29.40	40.50		57.50	2262
	25	36.75	43.72		62.08	2201


PUMP PERFORMANCE CHARACTERISTICS
4' DIAM. PUMP
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
30
CRAFT SPEED ~ MPH
SHP
300
250
200
150
100
75
100


PUMP PERFORMANCE CHARACTERISTICS
PUMP
PROPULSIVE COEFFICIENT
50
40
30
20
10
0
25
20
15
10
0
40
80
120
160
200
240
280
320
PUMP SHAFT HORSEPOWER


PUMP PERFORMANCE CHARACTERISTICS
PUMP RPM
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
80
120
160
200
240
280
320
PUMP SHAFT HORSEPOWER
25
20
15
10
0

APPENDIX F



PROPOSED PUMP - 16" DIAM.

ESTIMATED PERFORMANCE (POWER LIMIT)

CALCULATION NOTES

V_{MPH} = CRAFT SPEED ~ MPH (NOMINAL VALUES)

SHP_{14} = POWER TO 14" PUMP ~ HP (NOMINAL VALUES)

SHP_{16} = POWER TO 16" PUMP = $SHP_{14}\left(\frac{16}{14}\right)^2$

T_{14} = JET THRUST, 14" PUMP ~ #A (FROM ESTIMATED PERFORMANCE CALCS, 14" PUM

T_{16} = JET THRUST, 16" PUMP = $T_{14}\left(\frac{16}{14}\right)^2$

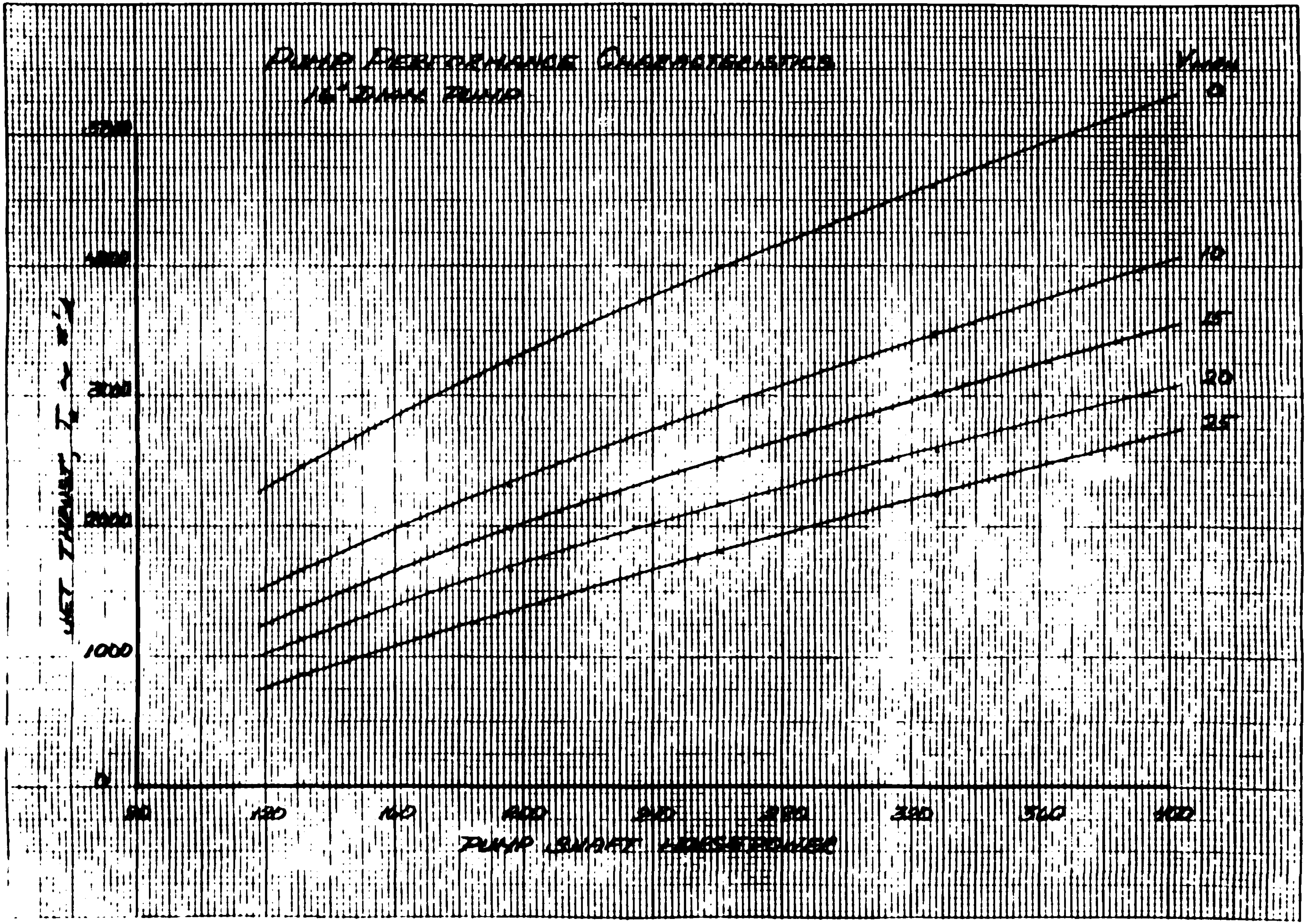
N_{14} = PROP RPM, 14" PUMP

N_{16} = PROP RPM, 16" PUMP = $N_{14}\left(\frac{14}{16}\right)$

Estimated Performance (Power Limit)

Calculation

V_{MPH}	SHP_N	SHP_G	T_N	T_G	N_N	N_G	SHP_G	T_G
0	100	131	1878	2453	1551	1357	200	3330
	150	196	2489	3257	1785	1562	300	4360
	200	261	3054	3989	1978	1731	400	5280
	250	327	3536	4618	2128	1862		
	300	392	3990	5211	2260	1978		
10	100	131	1281	1673	1629	1425	200	2380
	150	196	1777	2320	1857	1620	300	3250
	200	261	2236	2920	2032	1778	400	4040
	250	327	2658	3472	2182	1909		
	300	392	3039	3969	2308	2020		
15	100	131	1055	1378	1719	1504	200	2020
	150	196	1515	1979	1936	1694	300	2820
	200	261	1939	2533	2110	1846	400	3530
	250	327	2308	3015	2248	1967		
	300	392	2654	3466	2368	2072		
20	100	131	866	1131	1845	1614	200	1720
	150	196	1275	1665	2044	1788	300	2430
	200	261	1657	2164	2206	1930	400	3060
	250	327	1981	2587	2332	2040		
	300	392	2297	3000	2446	2140		
25	100	131	663	866	1984	1736	200	1350
	150	196	1027	1341	2164	1894	300	2080
	200	261	1386	1810	2320	2030	400	2720
	250	327	1718	2244	2452	2146		
	300	392	2043	2668	2573	2251		


PUMP PERFORMANCE CHARACTERISTICS
NET THRUST
1000
2000
3000
PUMP SHAFT HORSEPOWER
0
10
15
20
25

ESTIMATED PERFORMANCE (CAVITATION LIMIT)

CALCULATION NOTES

V_{MPH} = CRAFT SPEED ~ MPH (NOMINAL VALUES)

σ = CAVITATION INDEX (SELECTED VALUES)

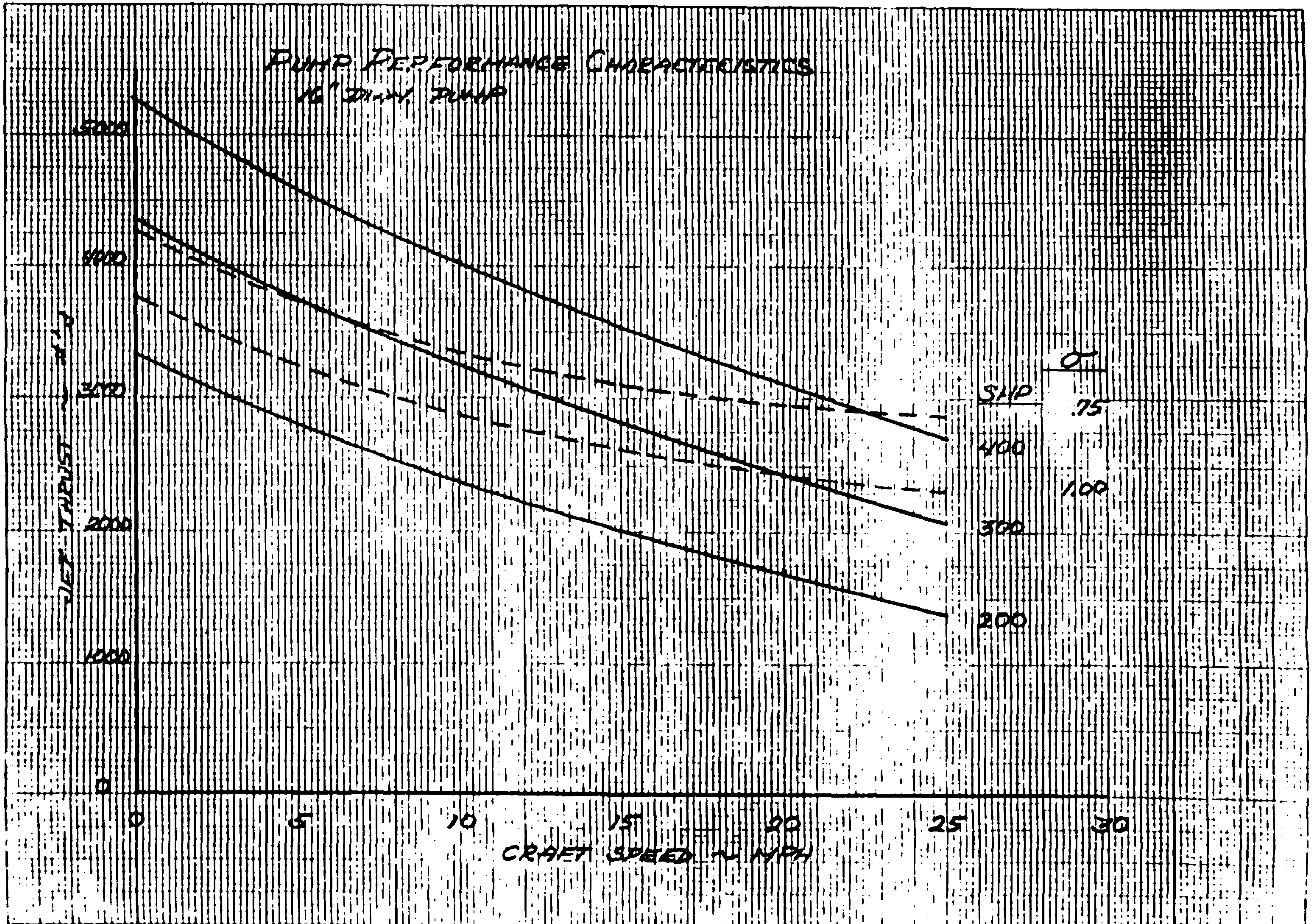
T_{14} = JET THRUST, 14" PUMP ~ #'s (FROM EST. PERF. 14" PUMP)

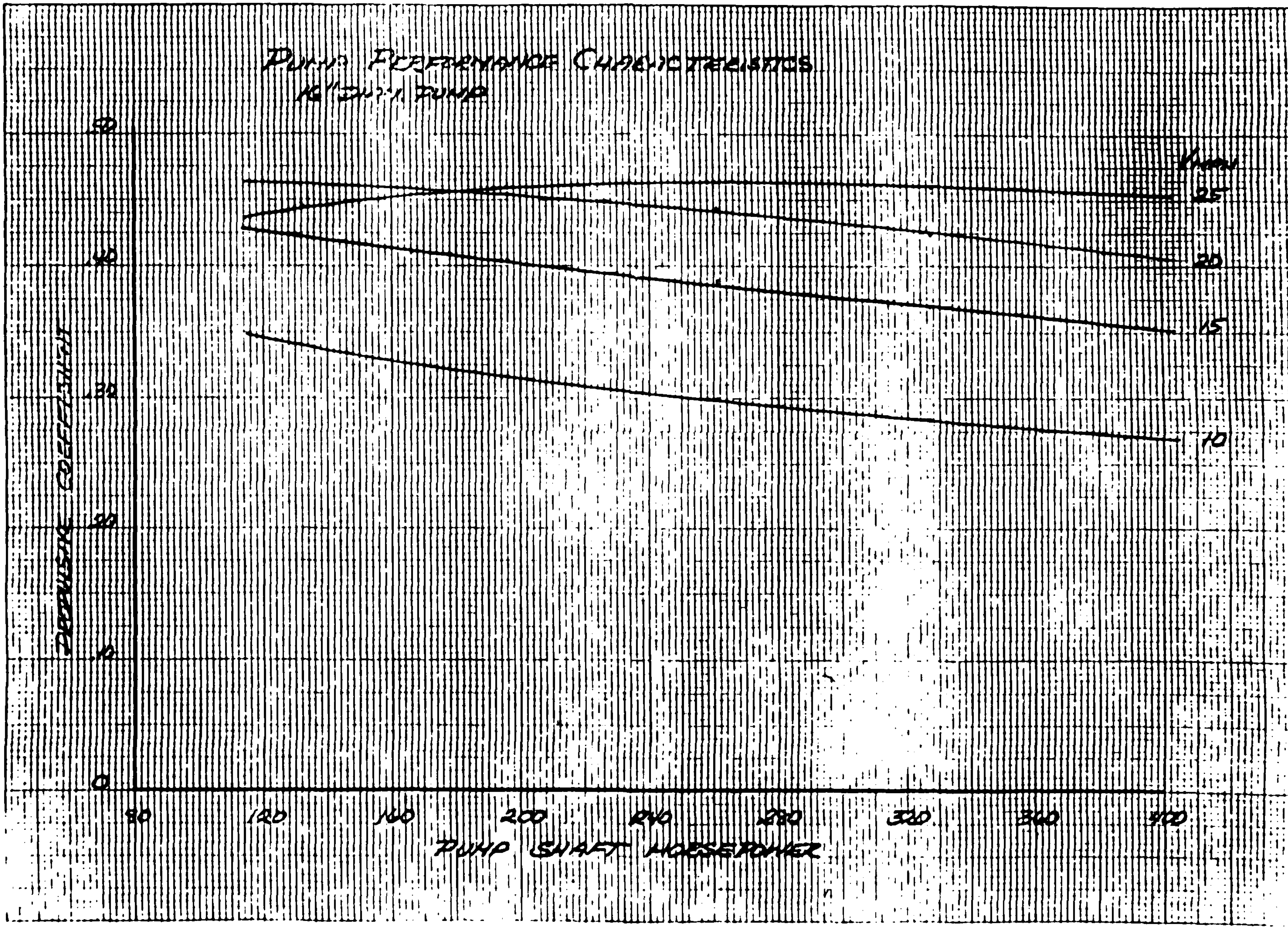
T_{16} = JET THRUST, 16" PUMP $= T_{14}\left(\frac{16}{14}\right)^2$

ESTIMATED PERFORMANCE (CAVITATION LIMIT)

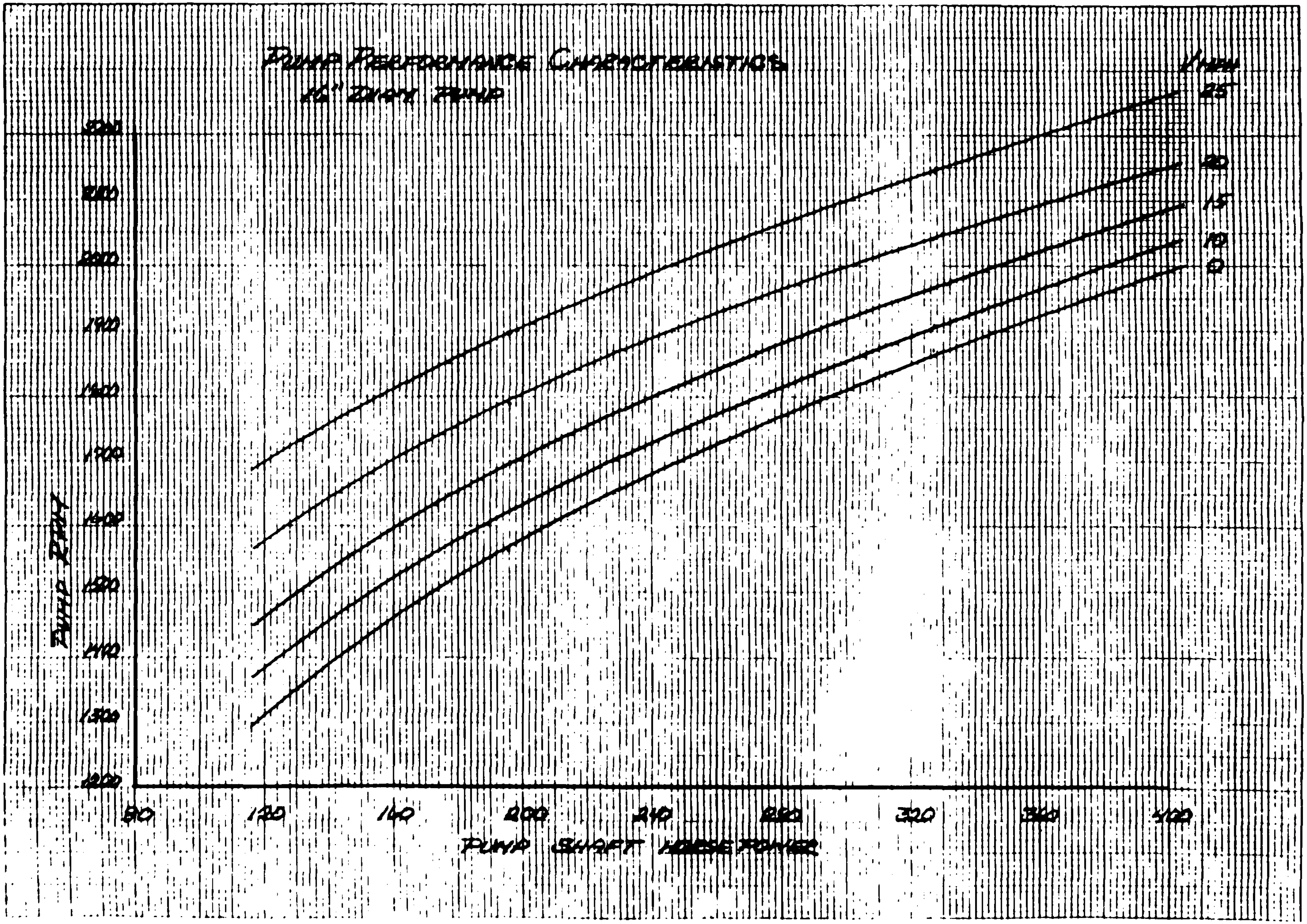
CALCULATION

V_{MPH}	σ	T_{14}	T_{16}
0	1.00	2892	3777
	.75	3264	4263
10	1.00	2210	2887
	.75	2560	3344
15	1.00	2012	2628
	.75	2375	3102
20	1.00	1872	2445
	.75	2262	2954
25	1.00	1773	2316
	.75	2201	2875


PUMP PERFORMANCE CHARACTERISTICS
16" DIAM. PUMP
JET THRUST ~ F_{T} #
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
30
CRAFT SPEED ~ MPH
SHP
400
300
200
σ
.75
1.00



PUMP PERFORMANCE CHARACTERISTICS
PROPULSIVE COEFFICIENT
.50
.40
.30
.20
.10
0
25
20
15
10
80
120
160
200
240
280
320
360
400
PUMP SHAFT HORSEPOWER


PUMP PERFORMANCE CHARACTERISTICS
16" DIAM. PUMP
25
20
15
10
0
PUMP RPM
80
120
160
200
240
280
320
360
400
PUMP SHAFT HORSE POWER

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